Atmospheric Pressure Plasma Based Flame Control and Diagnostics

Richard Miles

Department of Mechanical and Aerospace Engineering

Princeton University

Atmospheric Pressure Plasma Based Flame Control and Diagnostics

Atmospheric Pressure Plasma Based Flame Control and Diagnostics

Supported by AFOSR MURI

Fundamental mechanisms, predictive modeling, and novel aerospace applications of plasma assisted combustion.

Mechanical and Aerospace Engineering

Applied Physics Group

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2015**	2. REPORT TYPE	3. DATES COVERED **00-00-2015 to 00-00-2015**
4. TITLE AND SUBTITLE **Atmospheric Pressure Plasma Based Flame Control and Diagnostics**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Princeton University,Department of Mechanical & Aerospace Engineering,Applied Physics Group,Princeton,NJ,08544**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **AFOSR MURI 2015 Fifth Year Review Meeting**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**49**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Research Group

Graduate Students
- Nathan Calvert
- Tat Loon Chng
- Matthew Edwards*
- Chris Limbach*
- Sean McGuire*
- Christopher Peters
- Yibin Zhang

Recently Graduated
- Nick DeLuca (MS 2013)
  - USMC
- James Michael (Ph.D. 2012)
  - Iowa State U.
- Emanuel Stockman (Ph.D. 2009)
  - Lockheed Martin

Research Scientists
- Arthur Dogariu
- Mikhail Shneider*
- Andrey Starikovskiy*

Technical Staff
- Nick Tkash

Visiting Research Collaborators
- Albina Tropina (Kharkiv, Ukraine)
- Martiqua Post (US Air Force Academy)

Visiting Graduate Students
- Nina (Jaibao) Li (Tsinghua University)
- Kevin Prieur (École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris)
- Carmen Guerra Garcia (MIT)

* Giving related talks here at SciTech 2015

Significant MURI Accomplishments

- Single pulse (10 nsec) quantitative Filtered Rayleigh imaging of temperature fields
- Pulsed microwave control of flames
  - Greater than 20% Flame speed enhancement
    - Coupling efficiency greater than 50%
    - < 10% of the flame power
  - Factor of two reduction in equivalence ratio limit.
- Radar REMPI measurement of NO and radicals in flames.
- Pulsed microwave coupling to laser pre ionization
  - Distributed ignition
- Femtosecond Laser Electronic Excitation Tagging (FLEET) for velocity and temperature profiles

Filtered Rayleigh Scattering

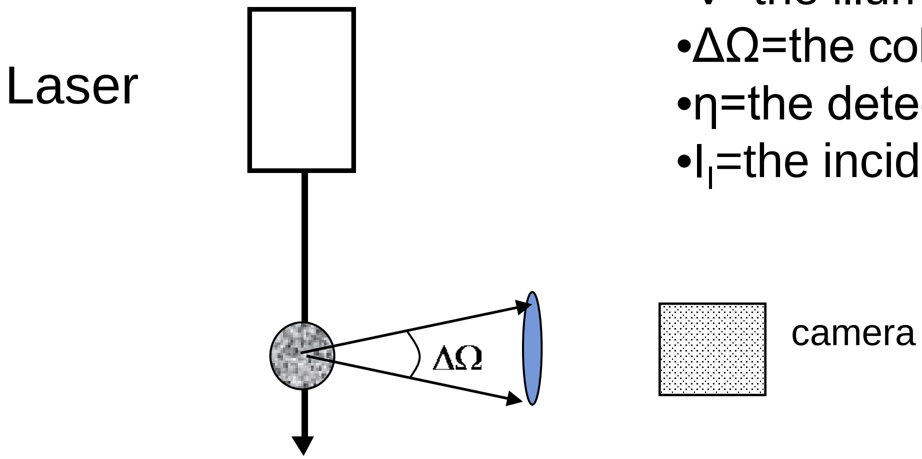
for Quantitative Temperature Imaging
at constant pressure

Applied Physics Group
Princeton University

Rayleigh Signal

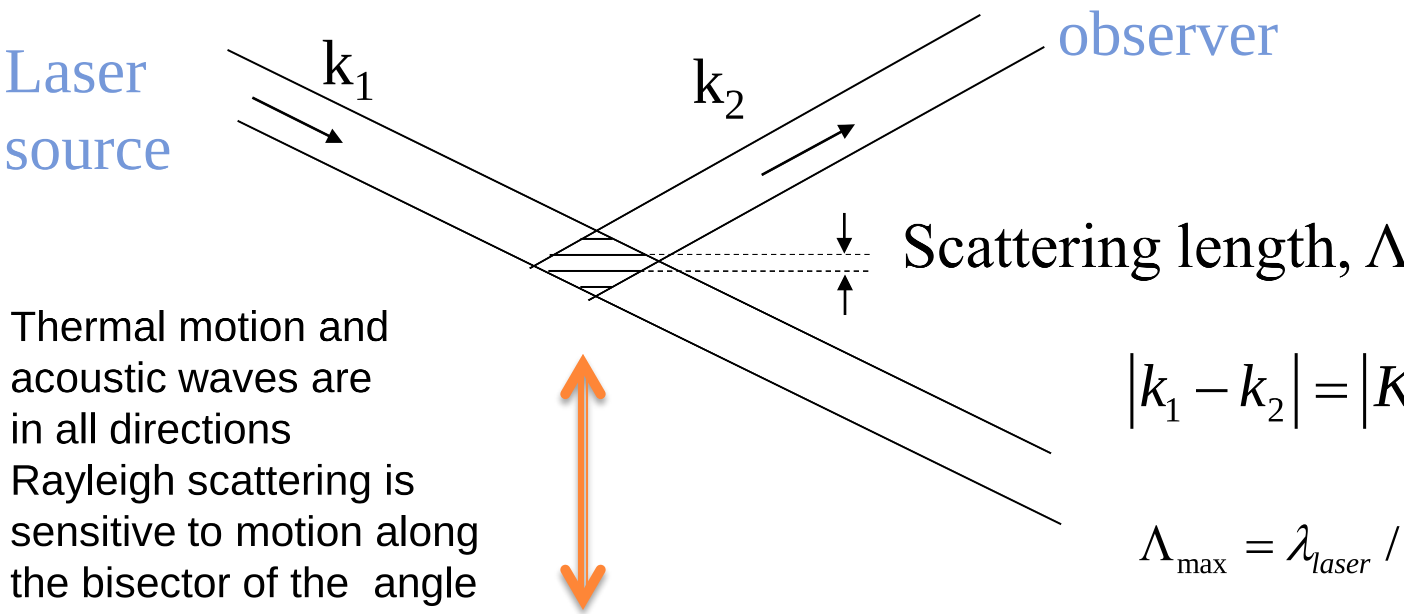
$$P_{DET} = \eta\, I_I\, NV \int_{\Delta\Omega} \frac{\partial \sigma_{ss}}{\partial \Omega} d\Omega$$

- N = the number of dipoles per unit volume
- V=the illuminated volume of the sample
- ΔΩ=the collection solid angle
- η=the detector and optical system efficiency
- I_I=the incident laser intensity



Rayleigh Scattering Interactions leading to line broadenting

- Y = scattering length / mean free path



$$\left|k_1 - k_2\right| = \left|K\right| = \frac{2\pi}{\Lambda}$$

$$\Lambda_{\max} = \lambda_{laser} / 2$$

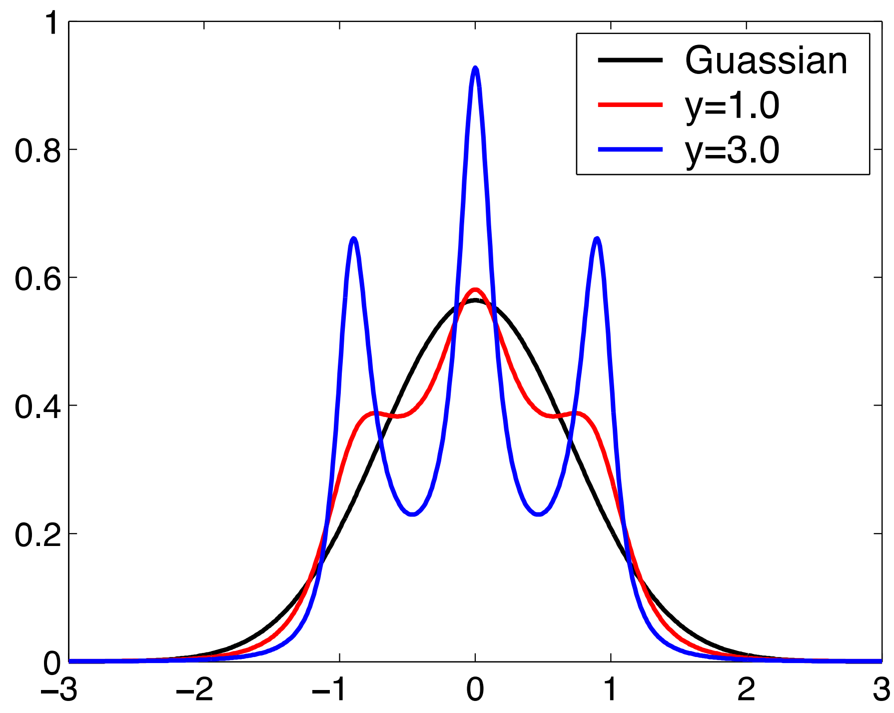
Thermal motion and acoustic waves are in all directions

Rayleigh scattering is sensitive to motion along the bisector of the angle between the source and detector

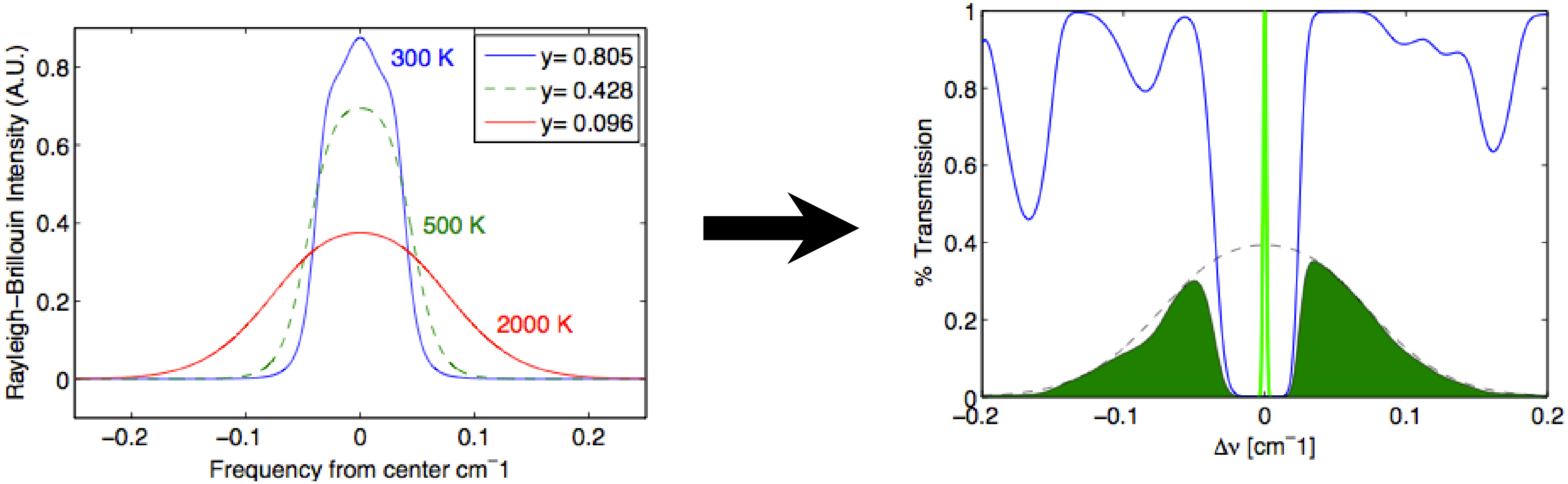
Line Broadening Regimes

- If Y < 1, then in the Knudsen Regime – no collective effects. The Rayleigh line is Gaussian in this regime –low density, high temperature

- If Y > 1, then in the hydrodynamic regime – collective effects dominate - high density , low temperature

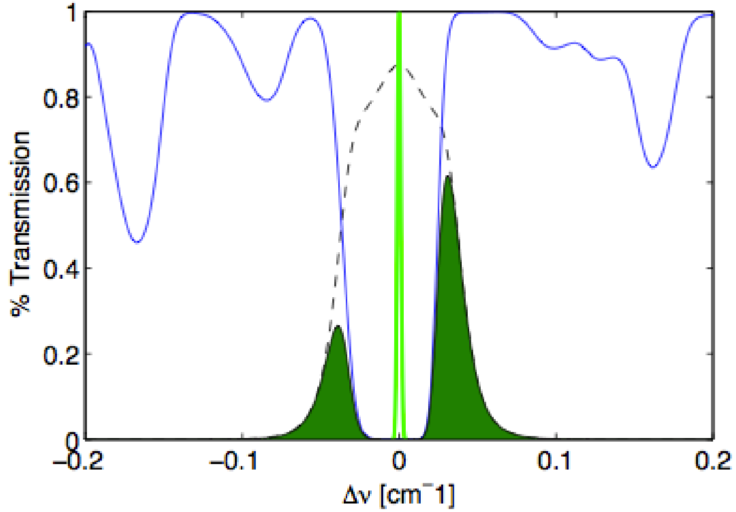


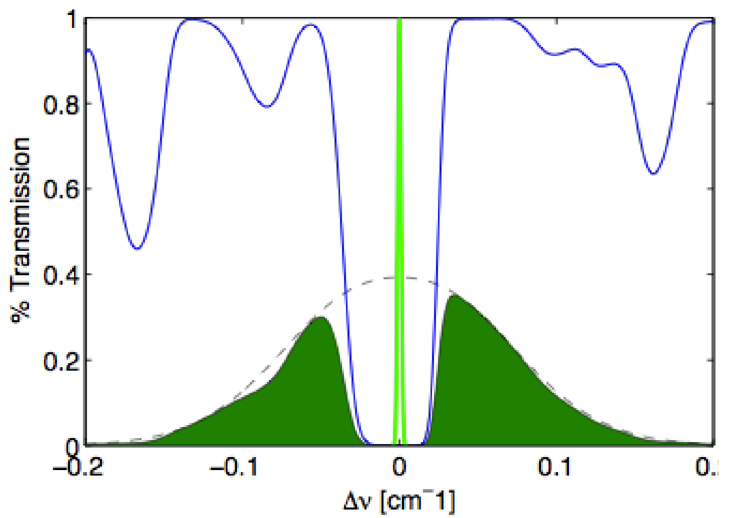
Temperature Imaging by Filtered Rayleigh scattering

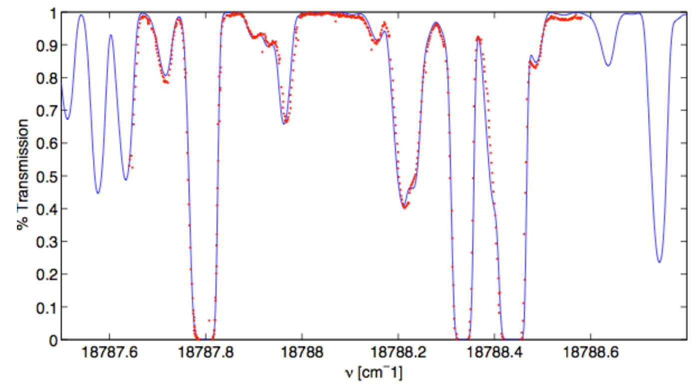


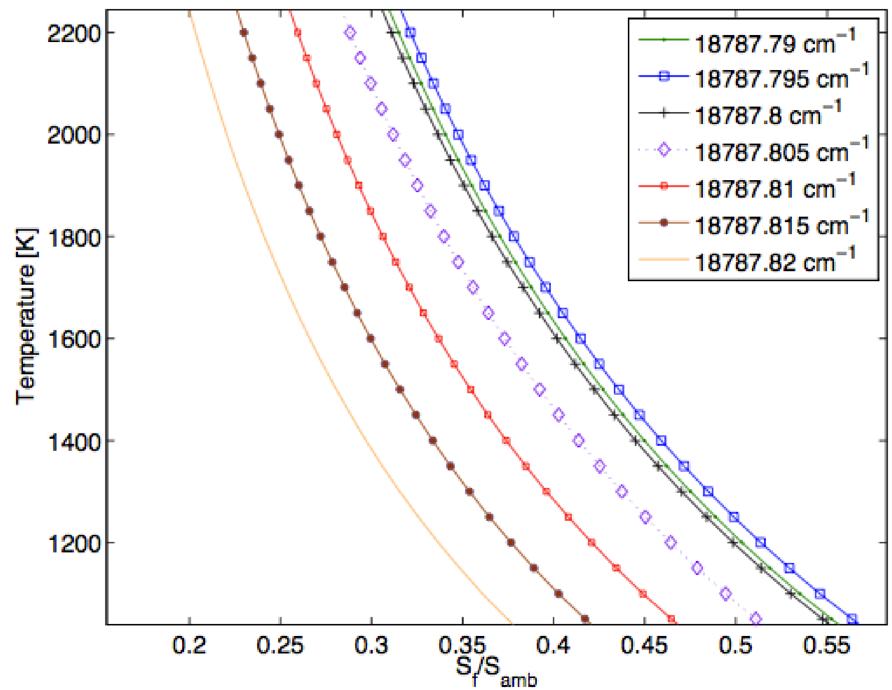
- Modeled Rayleigh-Brillouin Line Broadening (Pan S7)
- Narrow-linewidth molecular iodine filter to block background laser light. Eliminates particle and surface scattering
- Assuming constant pressure (one atmosphere for flame studies) and constant species (nitrogen is a good approximation) the signal coming through the filter is only a function of temperature
- Calibrate using the ratio of the signal from the high temperature to that of air or nitrogen at room temperature (often in the same frame)

FRS sensitivity to laser wavelength

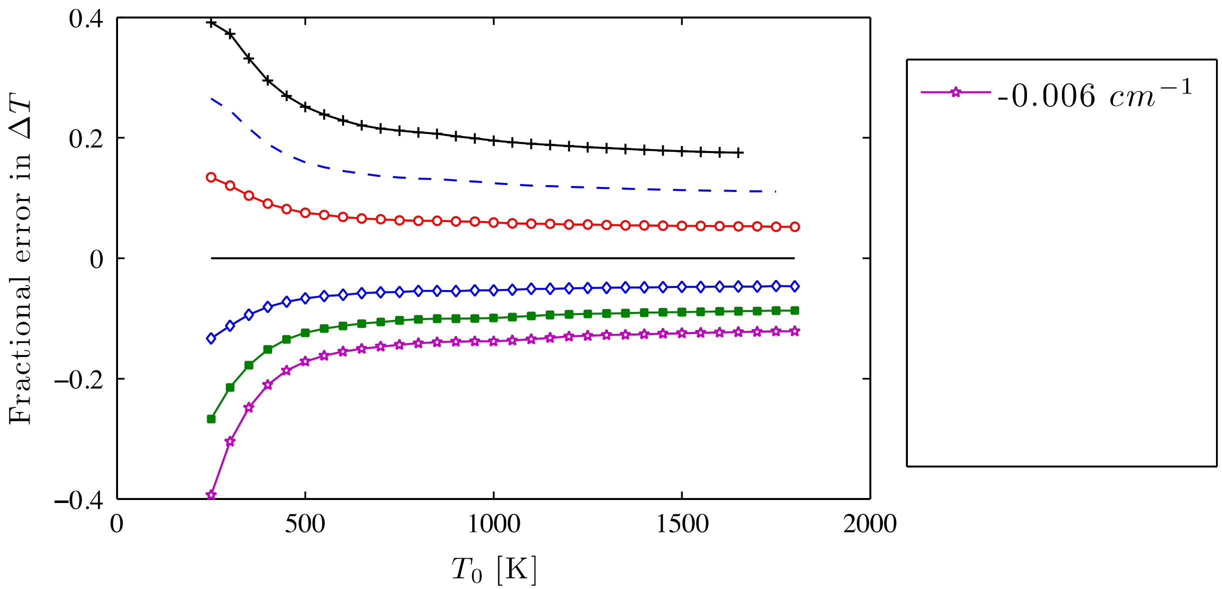








Differential Sensitivity with Temperature

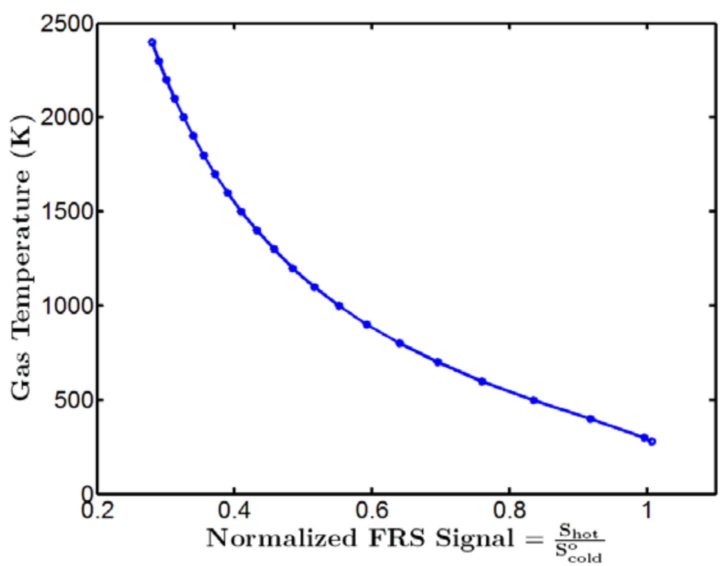


- At high temperature the slopes of the calibration curves are almost identical Leading to robust measurements of temperature differences above ~1000K
- Provides a single pulse (10 nsec) image of the temperature field

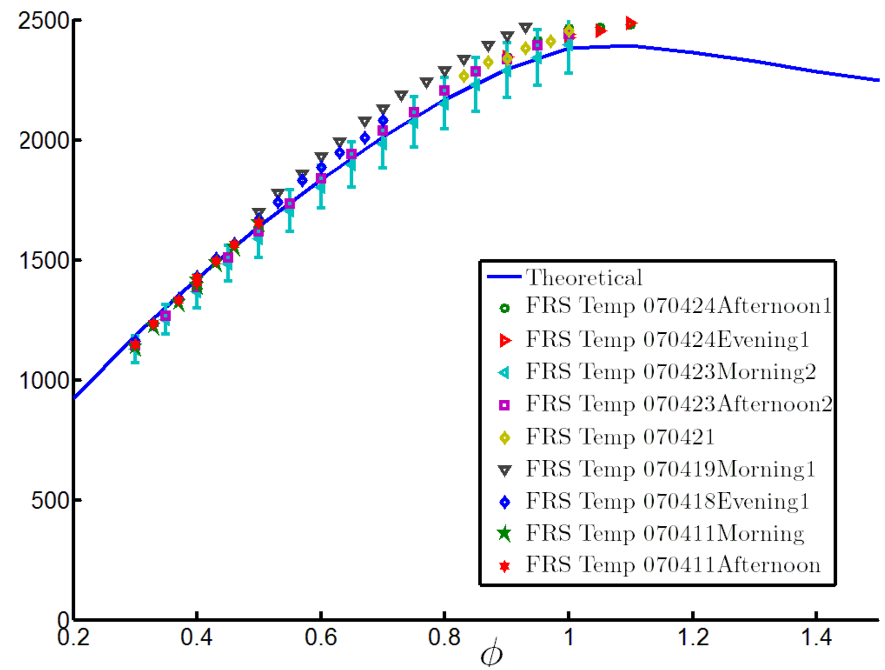
FRS Thermometry Calibration

- Research Technologies RD1x1 Hencken Burner
- With line scattering can obtain Rayleigh signal-to-background > 20:1
- Normalize flame Rayleigh scattering to that of N_2 co-flow
- Accuracy and precision better than 5%

Calibration



H_2/Air Hencken Burner Measurements with averaged FRS



Microwave interactions with flames

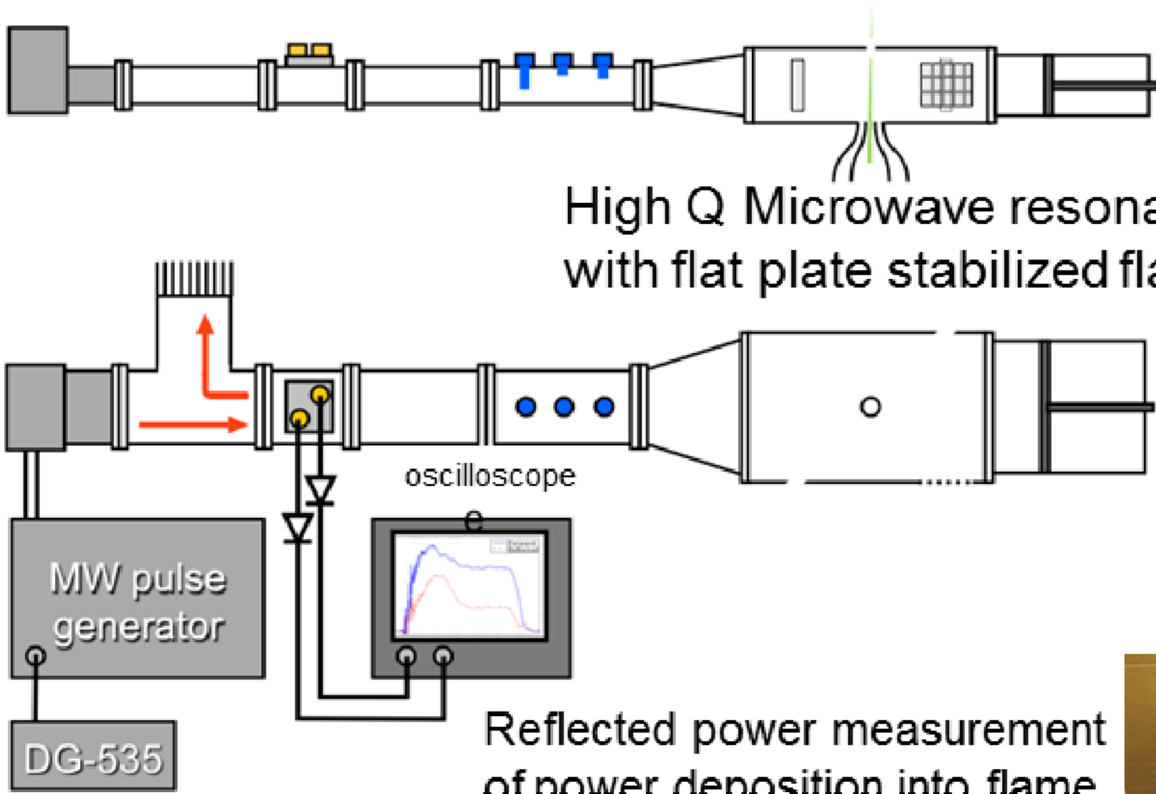
Couples to natural ionization in the flame

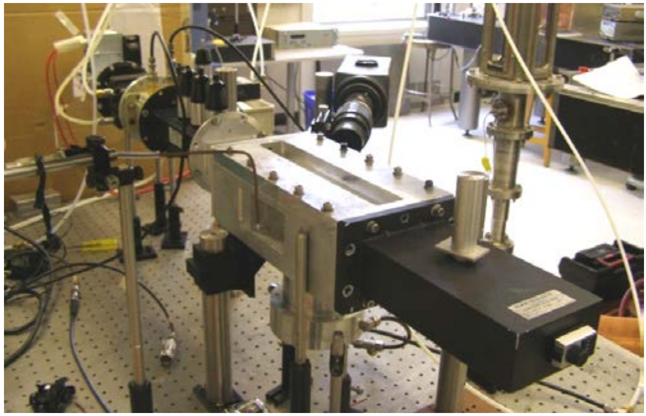
$CH + O \rightarrow HCO^{+} + \text{electron}$

Applied Physics Group

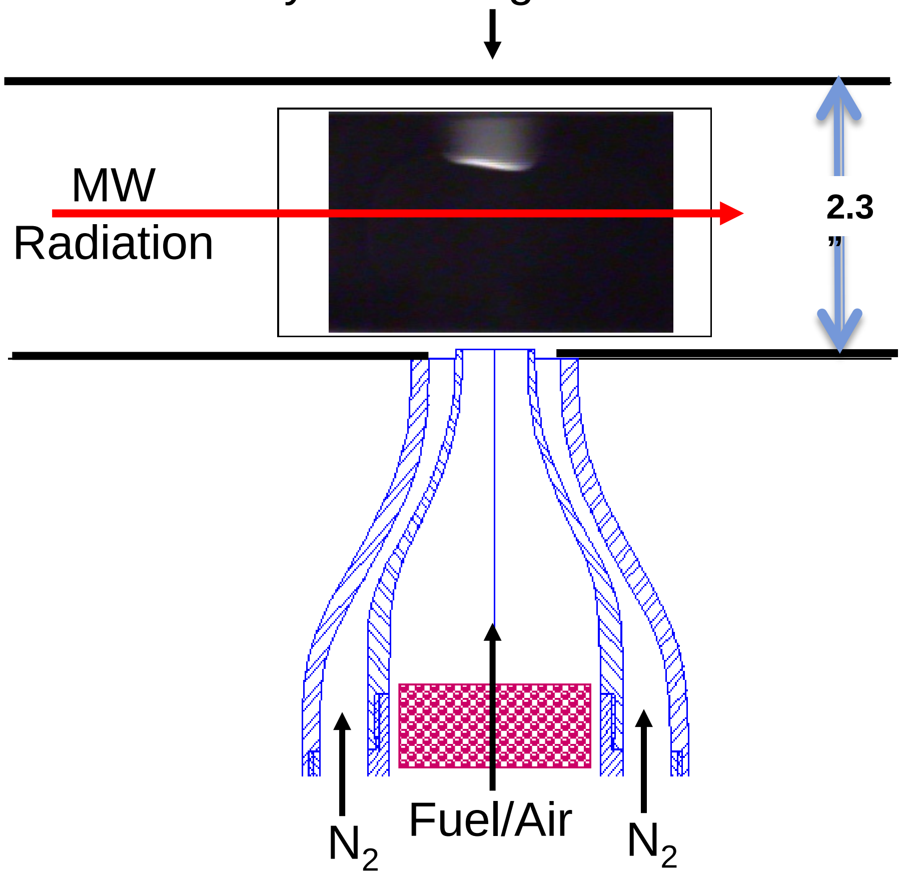
Princeton University

Microwave coupled Laminar Flame Set up

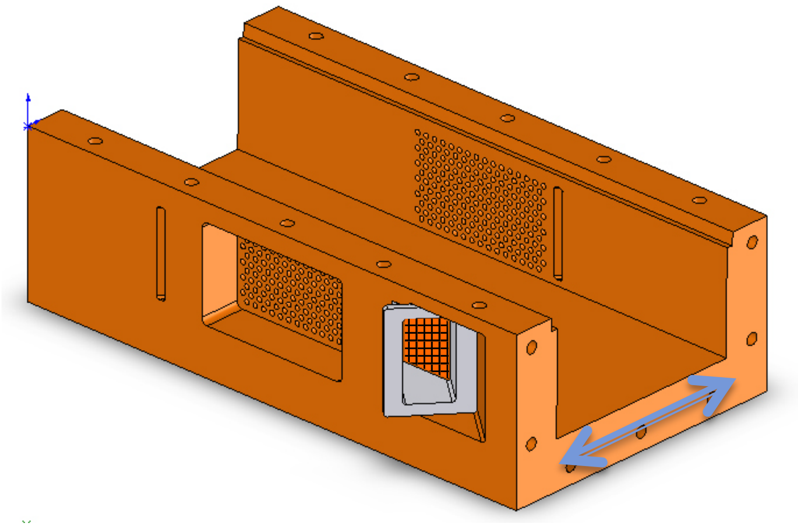




Experimental Setup: Laminar Burner



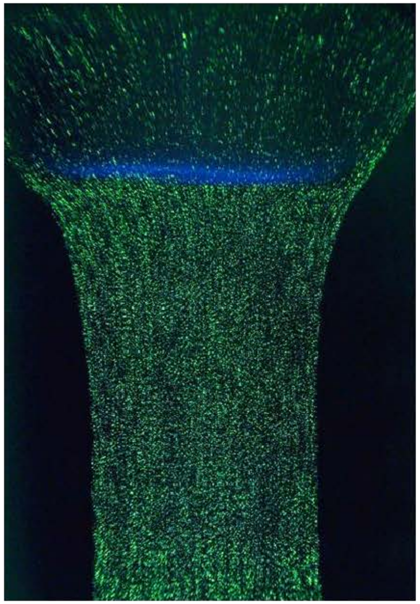
- Uniform velocity at exit
  $v_e < 100 \, {}^{cm}/_{s}$
- Large L/D ~ 3.8 leads to low strain rates
- Flame stabilized by aerodynamic strain rate
- Cavity limited optical access
  - ‘Meshed’ windows
  - Narrow laser slots



Flame Speed Enhancement with cw microwaves

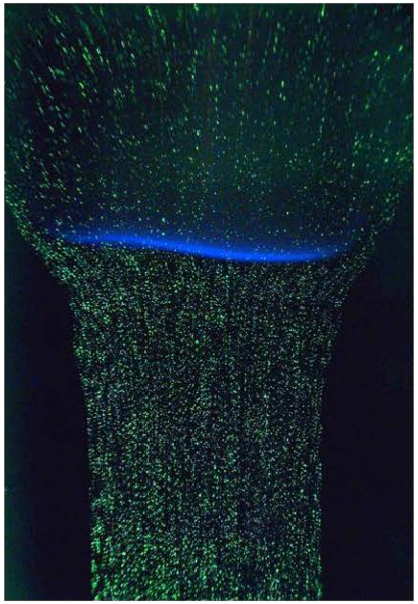
CH_4/Air

$v_{exit} = 85$ cm/s $\phi = 0.78$



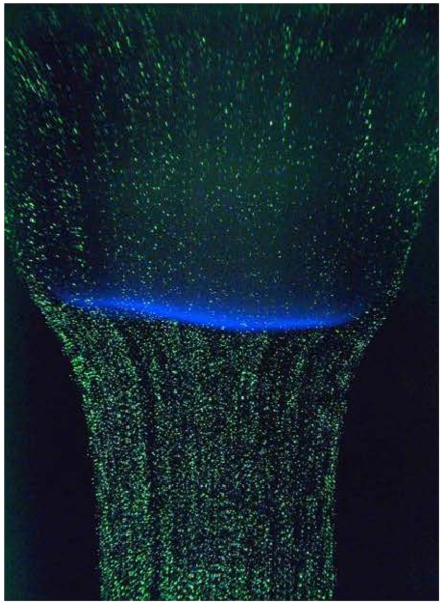
0 Watts

$S_{ref} = 33.7$ cm/s



700 Watts

$S_{ref} = 40.6$ cm/s

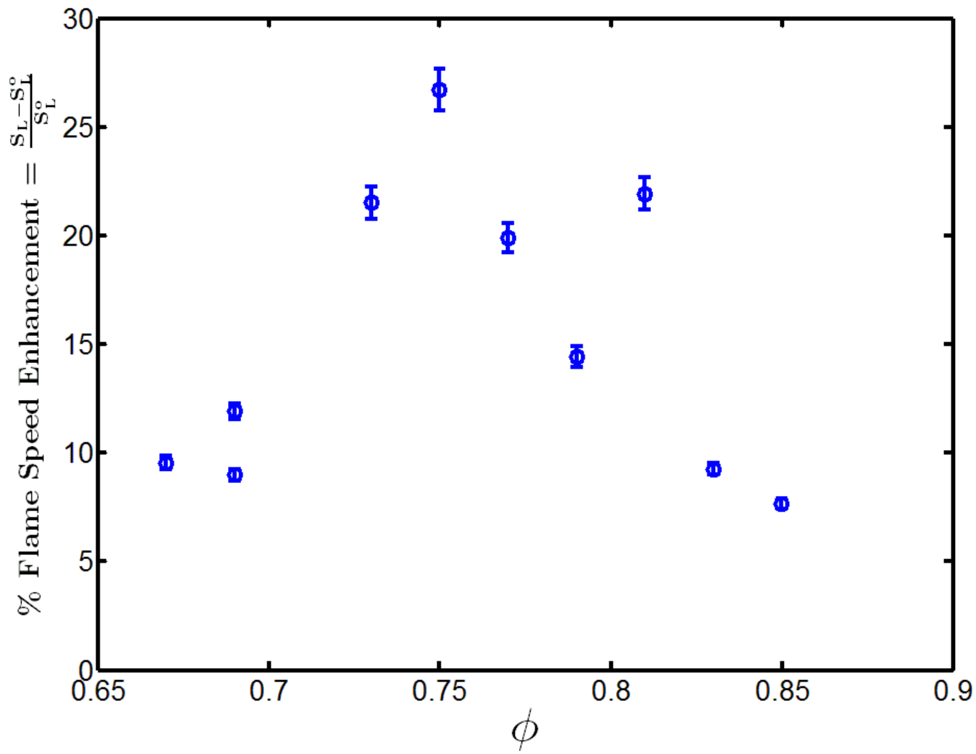


1200 Watts

$S_{ref} = 45.3$ cm/s

Flame Speed Enhancement

CH_4/Air laminar stagnation flame speed enhancement with 1.3kW cw-microwave radiation



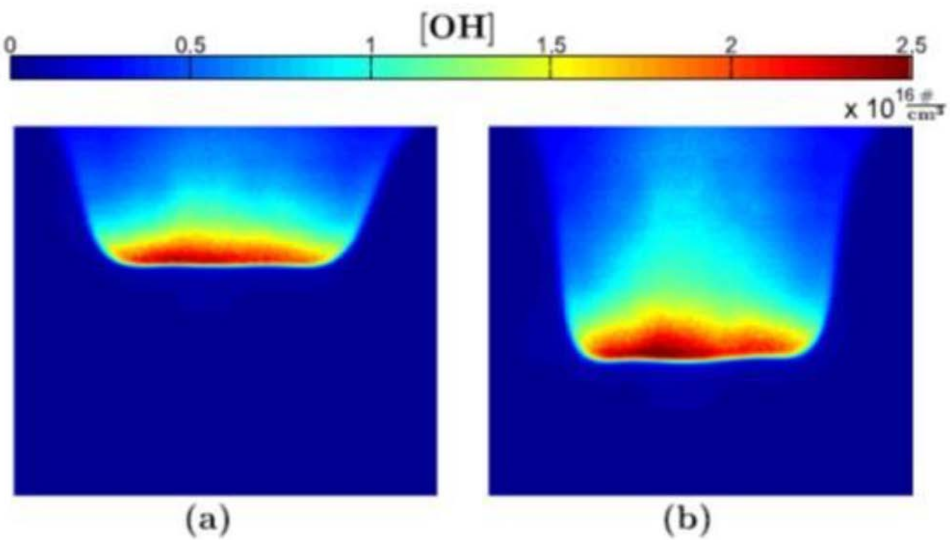
- 2% error in DPIV measurement propagates to ~4% error in flame speed enhancement percentage
- Peaking at ϕ=0.75 might be an outcome of experimental procedure

~25% enhancement seen with 1.3 kW magnetron, ~10-20W absorbed power

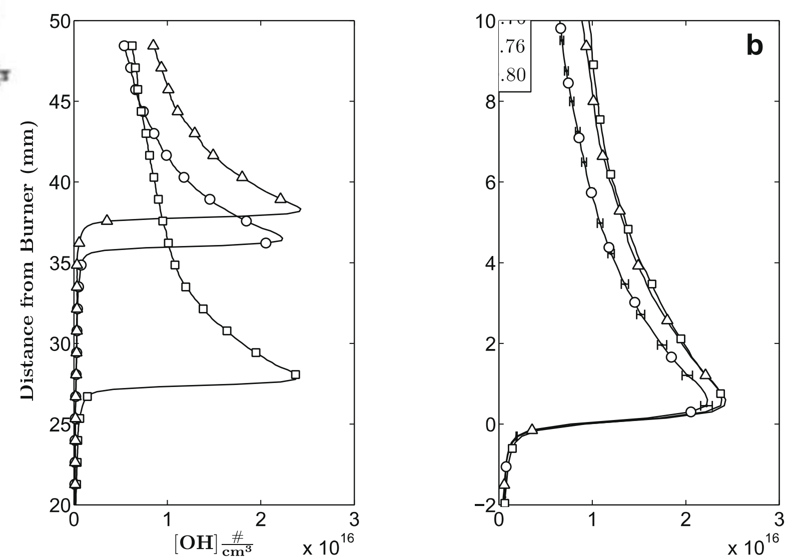
Princeton University

LiF Measurement of OH (with AFRL)

ϕ= 0.76

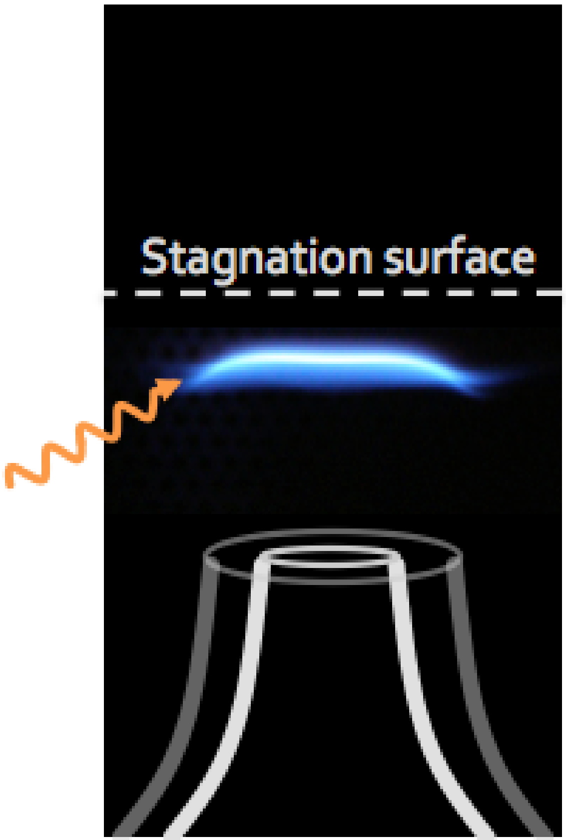


off on

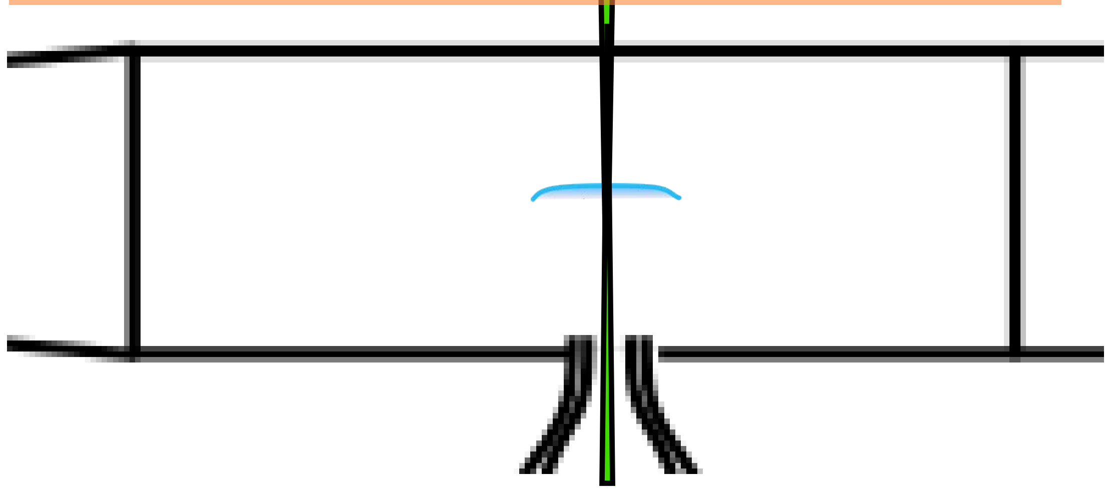


The OH level Is increased and the OH decay rate away from the flame front is reduced

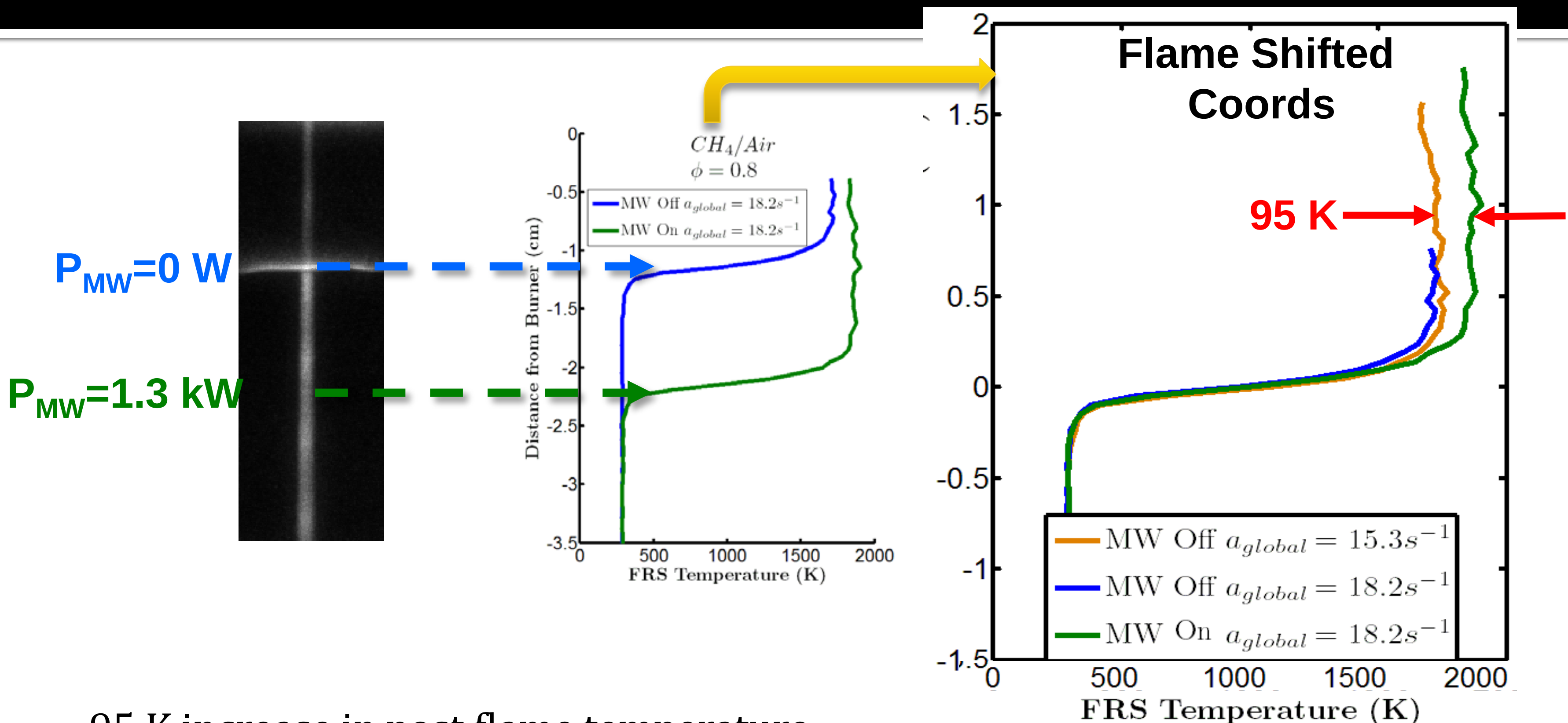
FRS Thermometry



- $U_{exit} \sim 60$ cm/s
- $D_{exit} = 0.6$ cm
- $\varphi = 0.6 - 0.9$
- 532 nm, injection seeded Nd:YAG for tunable, narrow linewidth



Line FRS Thermometry

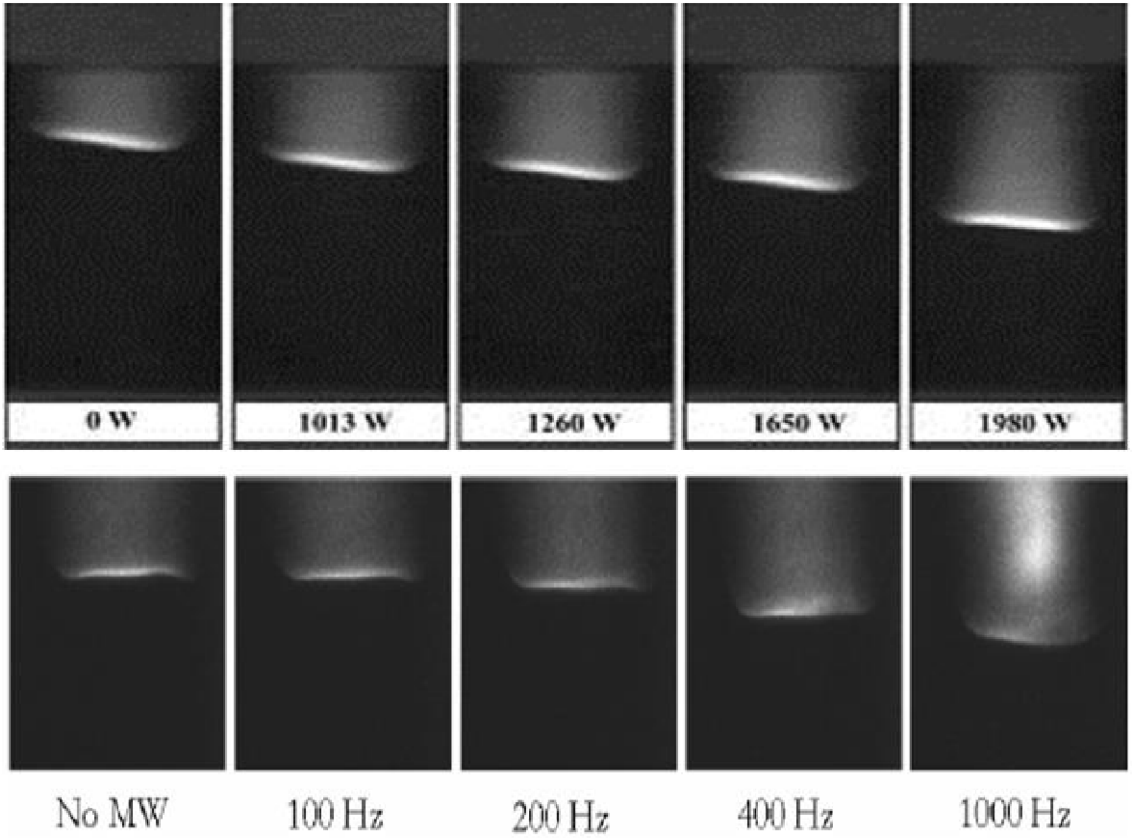


- 95 K increase in post flame temperature
- Temperature rise is just after flame sheet
  - Implies microwave energy deposition is in flame sheet

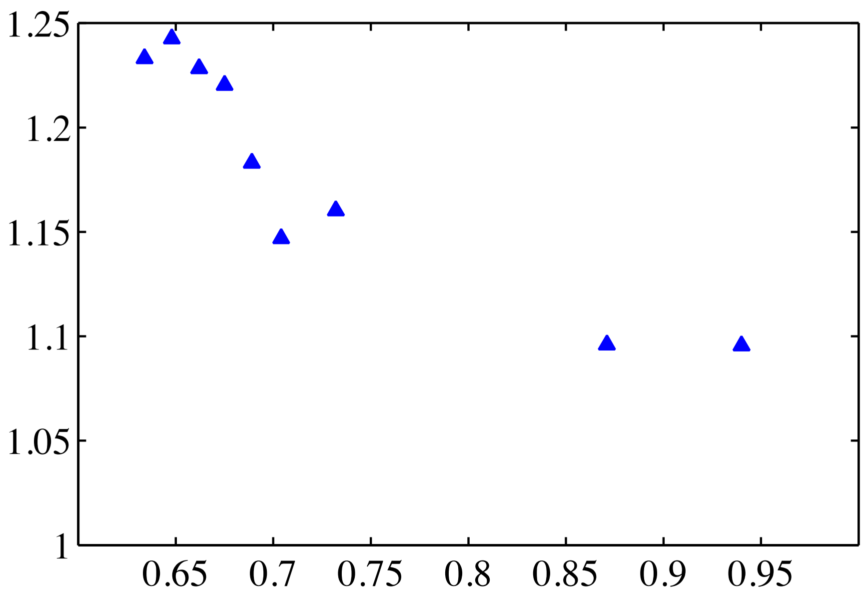
Microwave interactions with flames
Using microsecond duration pulsed microwaves

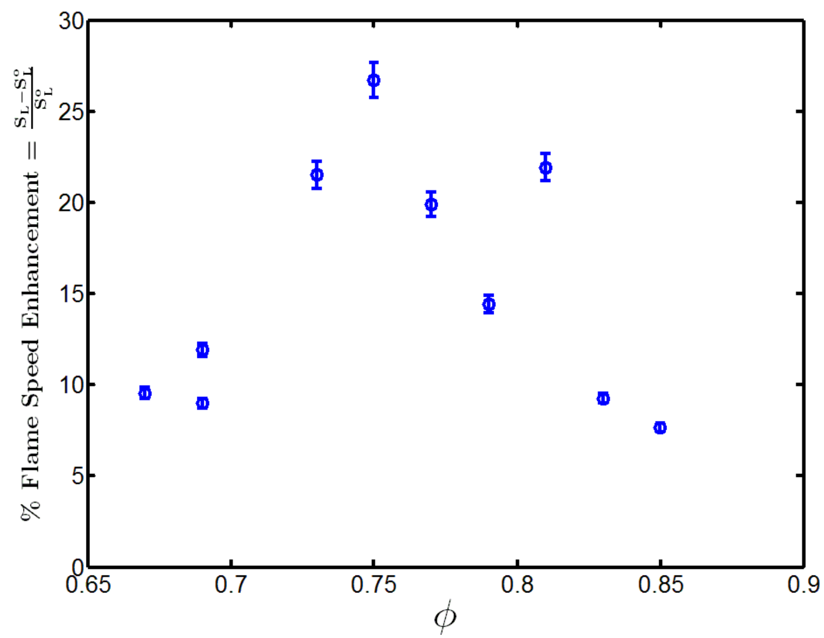
Applied Physics Group
Princeton University

Comparison of Flame Speed enhancement CW and pulsed microwaves



Flame Speed Enhancement with Pulsed Microwaves



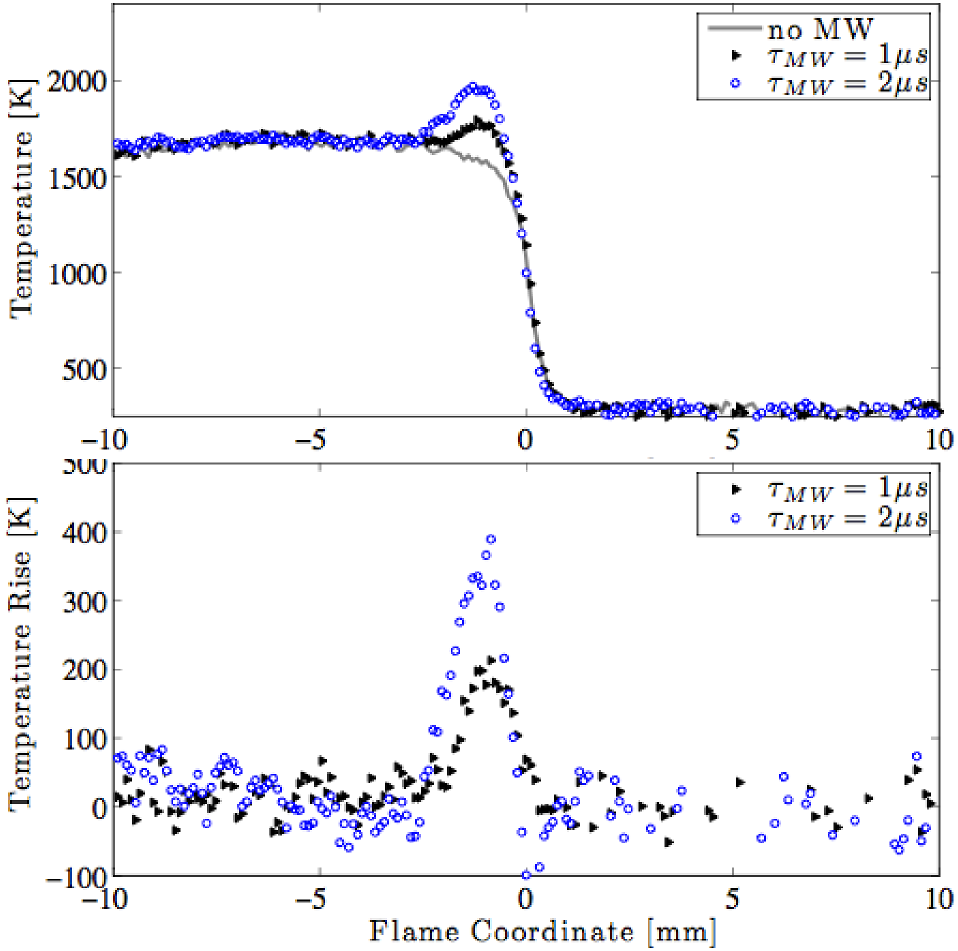


Pulsed 1 kHz, 5 mj/ pulse = 50 Watts

CW – 1.3 kW

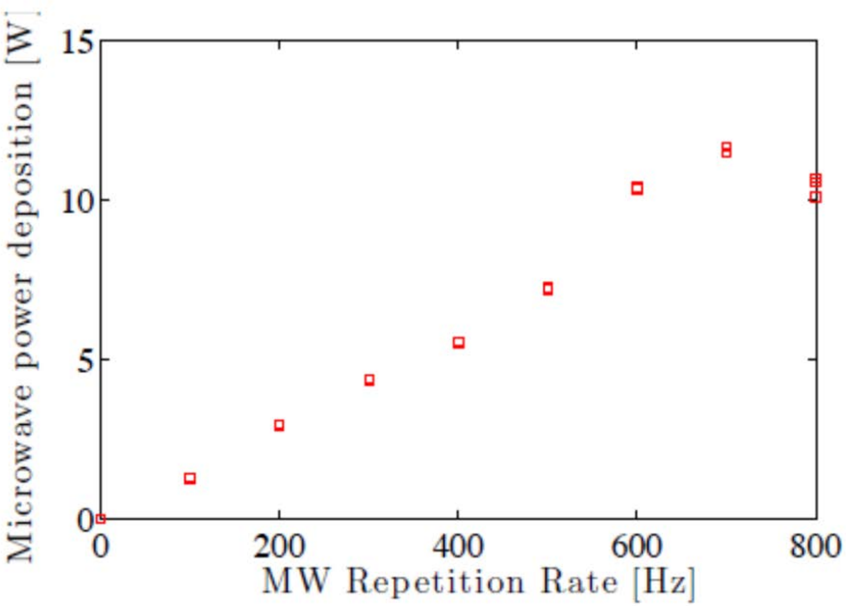
Reduction in average power by a factor of 26

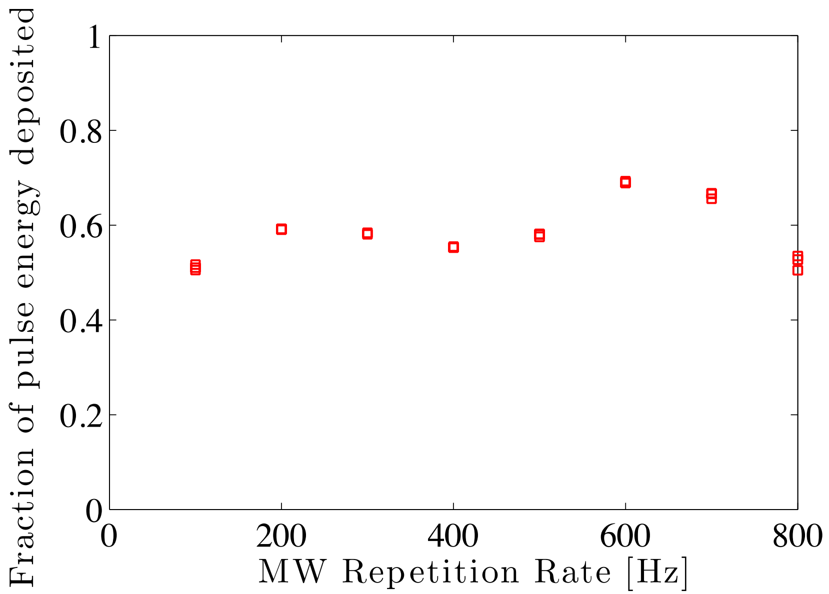
Single pulse temperature jump



- Deposition localized near flame front/reaction zone
- 25 mJ, 1 us pulse gives 200 K rise
- 50 mJ, 2 us pulse gives 350 K rise
- With 30 Watts average pulsed power the flame speed is enhanced as much as with a 1.3 kW continuous microwave
- Coupling efficiency is ~60%.

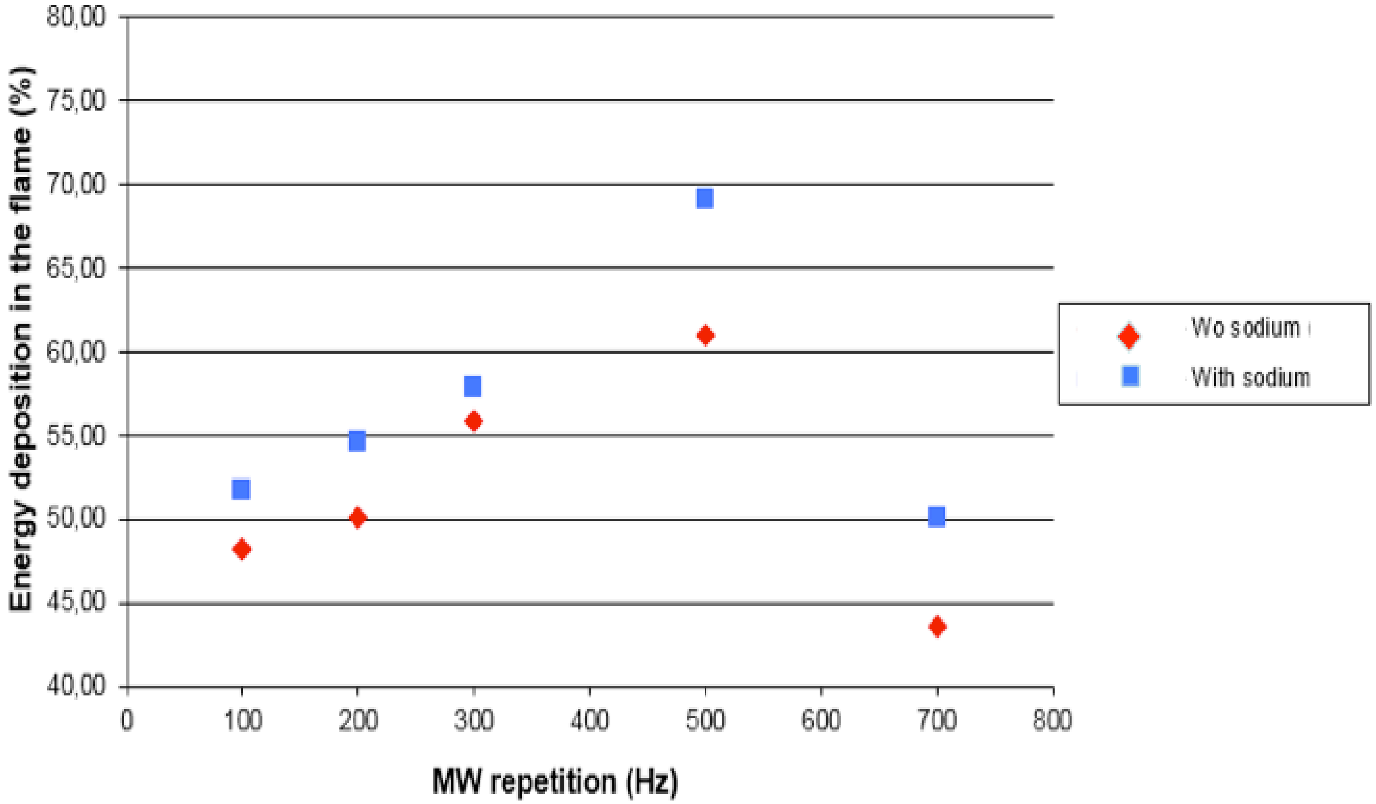
Power Deposition into flame from pulsed microwave system



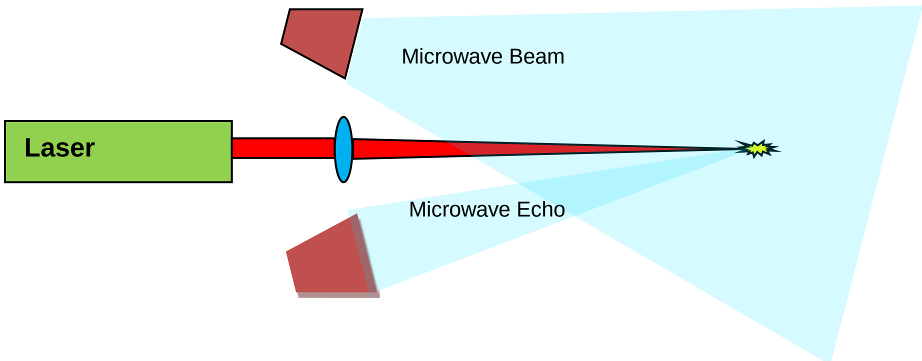


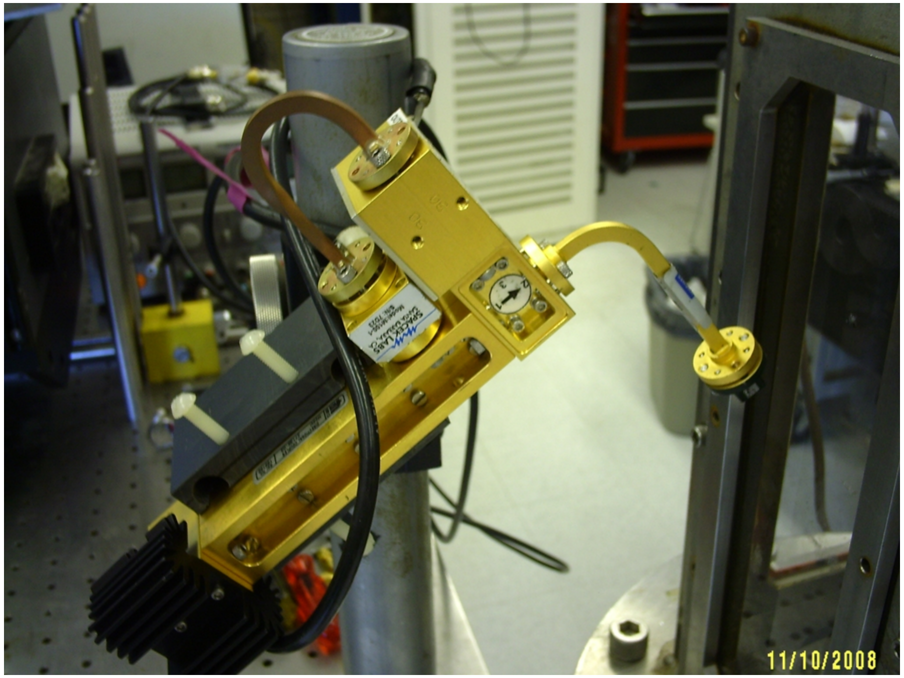
High efficiency coupling of pulsed microwaves

Further enhanced by seeding the fuel with sodium



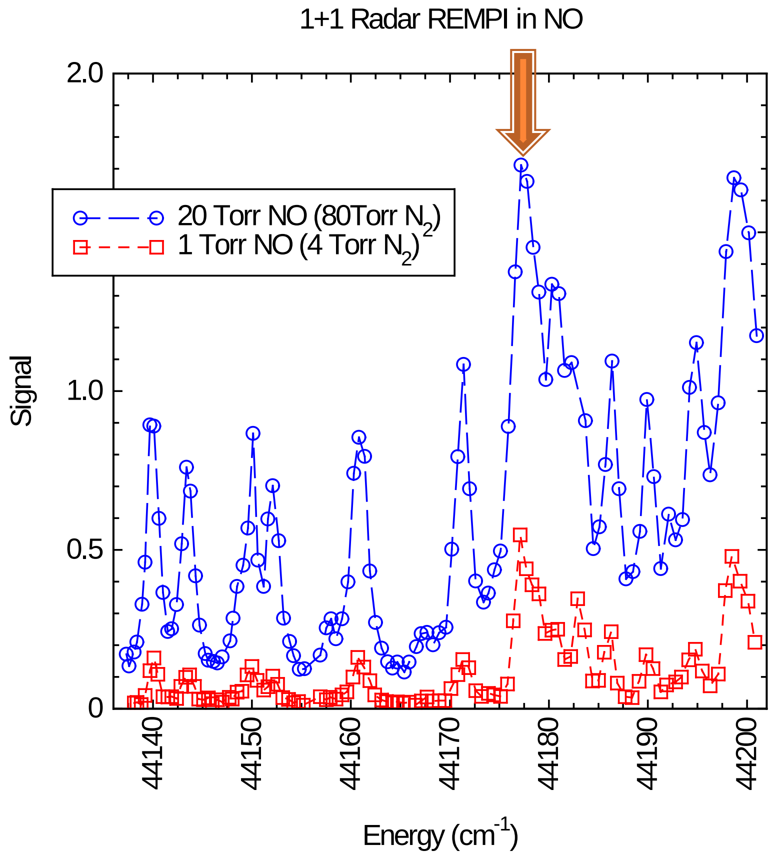
Radar REMPI measurement of NO

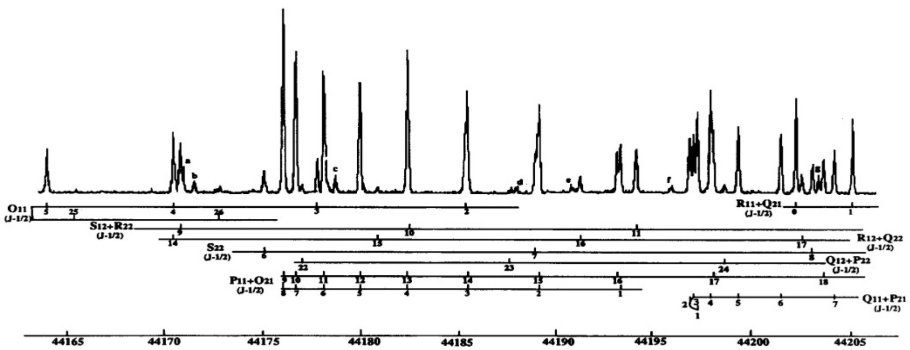




Microwave/laser measurement configuration. *The focused laser creates a small region of ionization and the microwaves are scattered from that region into the microwave detector.*

NO spectrum via 1+1 Radar REMPI



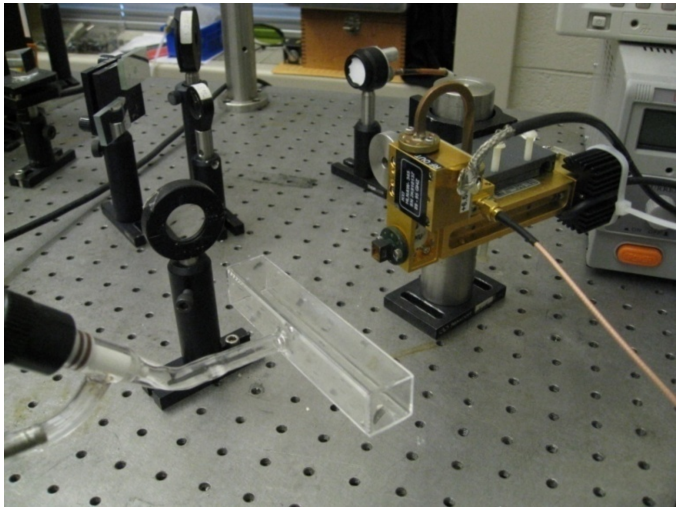


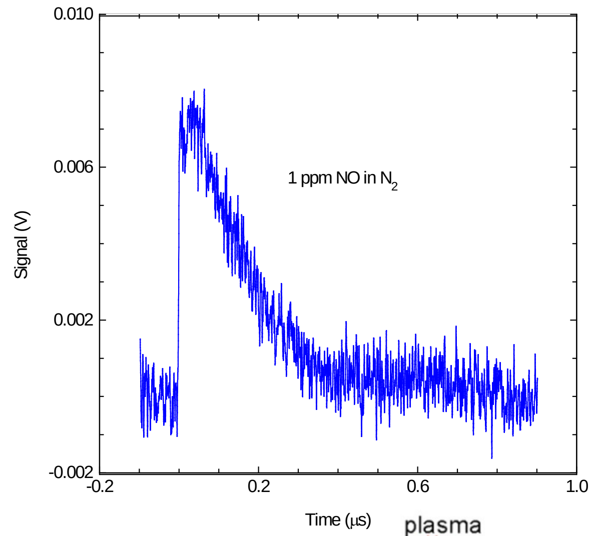
$A^2\Sigma^+ \leftarrow X^2\Pi$ molecular electronic transition

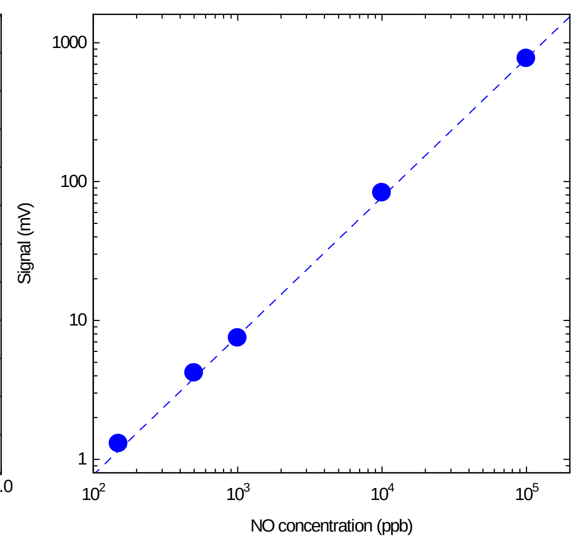
Princeton University

Luo et al., *Chem Phys*. **153**, 473 (1991)

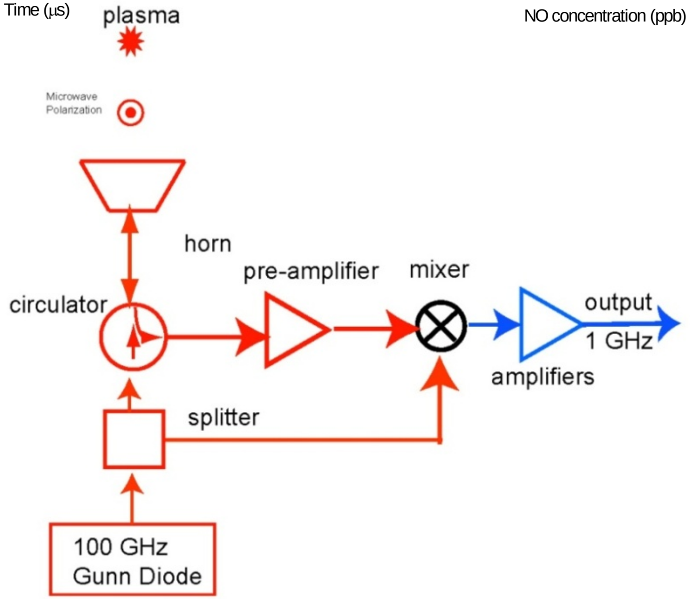
Radar REMPI Experimental Setup





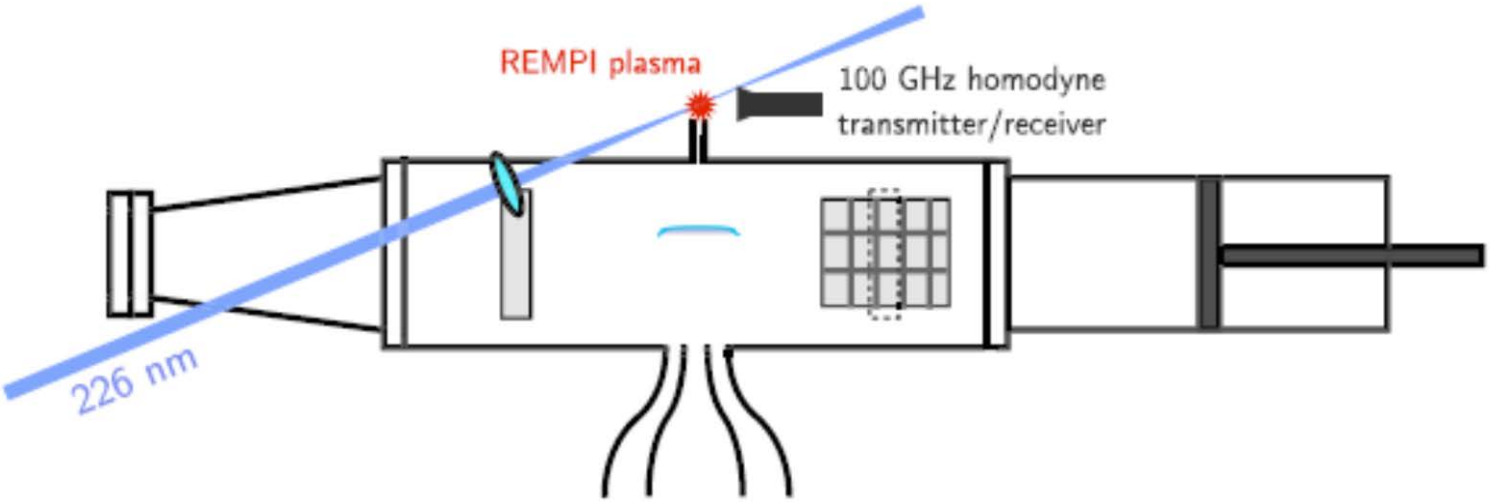


- 1+1 REMPI of NO with 226 nm laser
- 100 GHz probes the plasma.
- The mixer output is proportional to the scattering amplitude, hence electron density
- Linear signal from ppm to ppb
- Sub-nanosecond temporal resolution



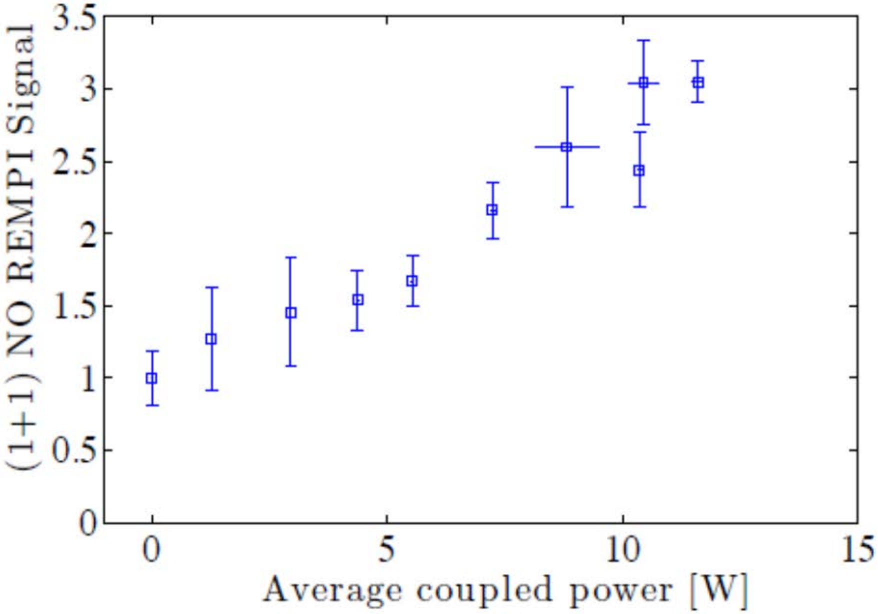
Princeton University

Nitroc Oxide production with pulsed microwaves using Radar REMPI



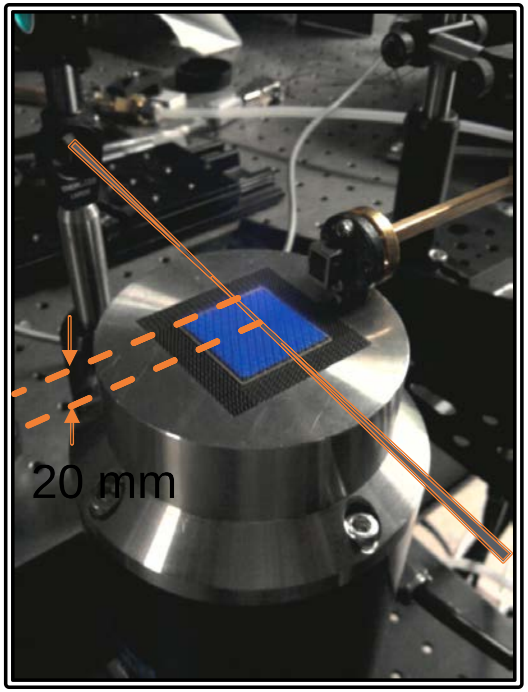
NO measured in the post flame product gas and averaged over time

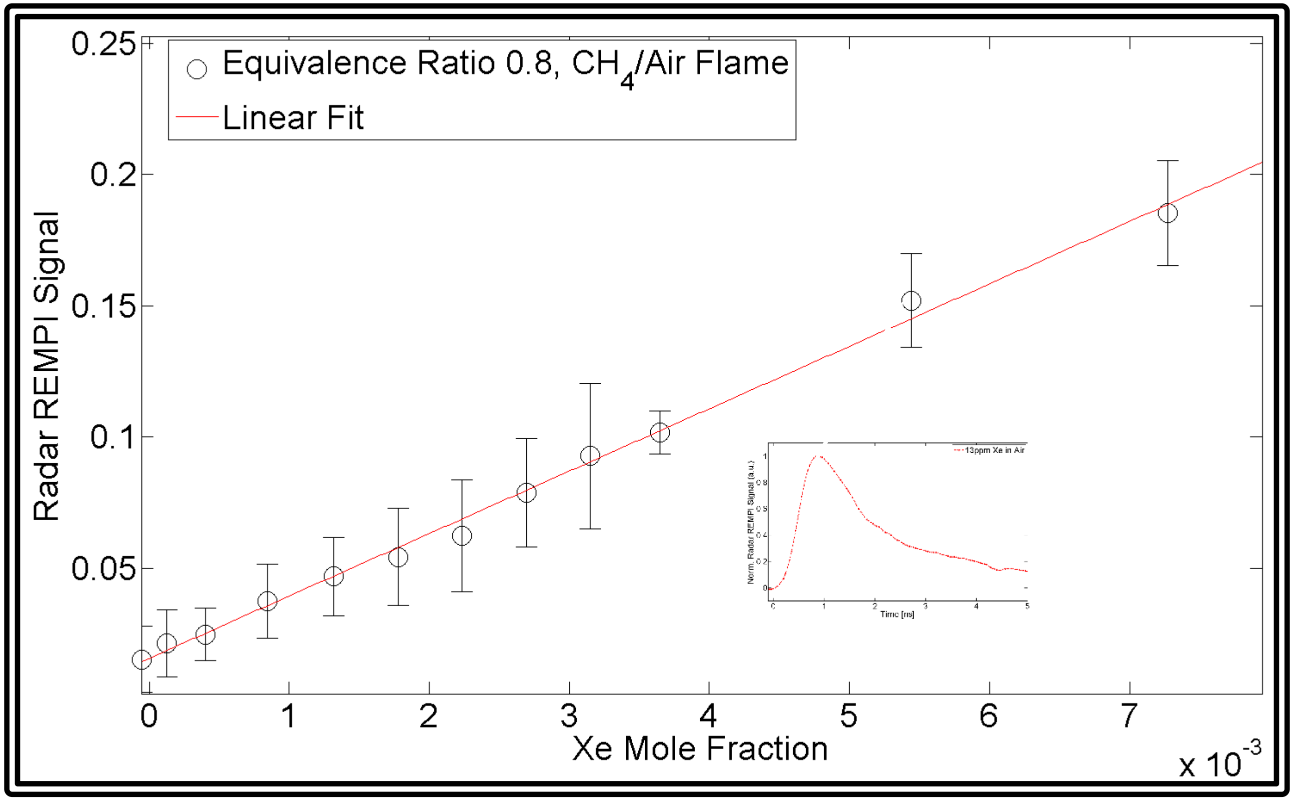
Increase of NO with microwave power



Predicted nitric oxide increase a a function of temperature over ϕ = 0.8 equilibrium

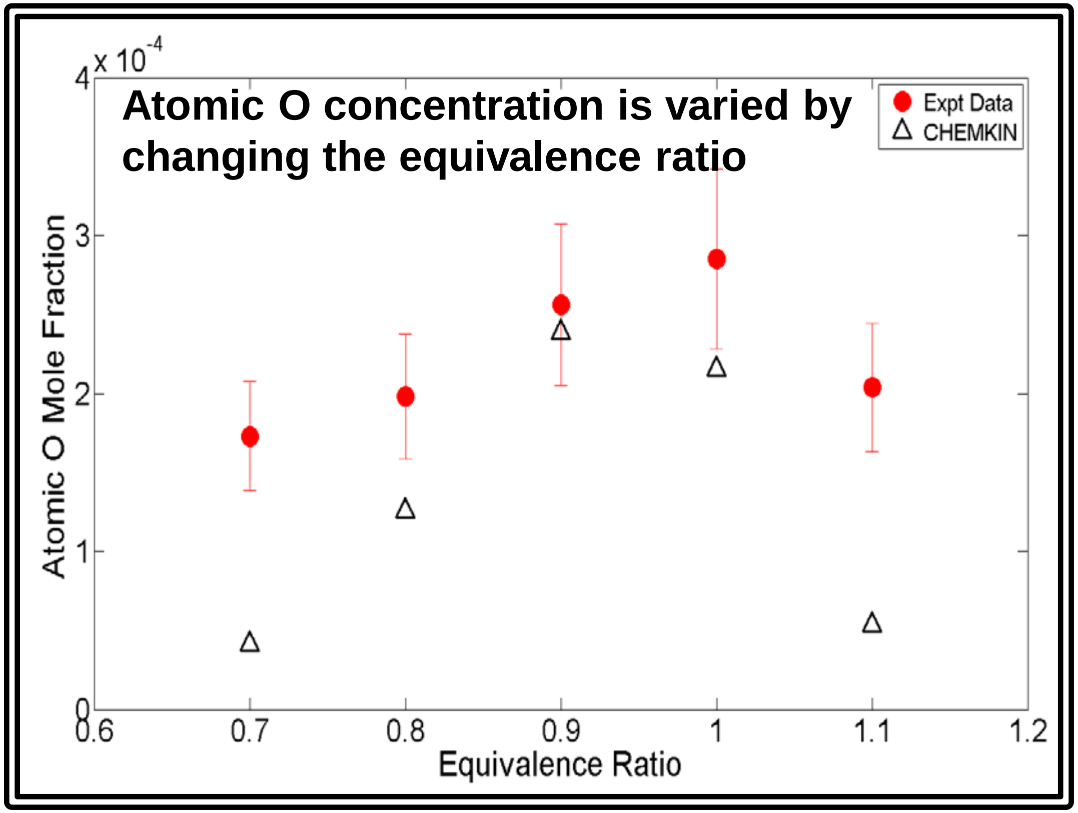
Xe Signal Linearity (CH_4/Air Flame)





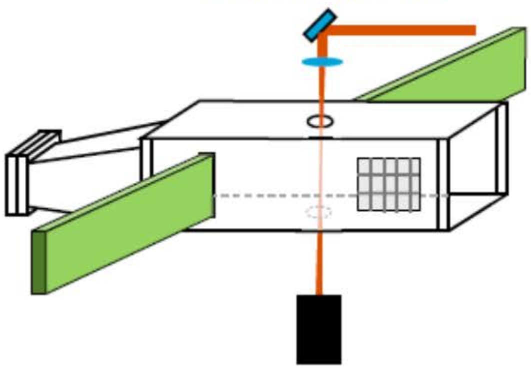
- Good signal linearity with Xe concentration observed at 20 mm above the burner surface, where atomic O concentrations are expected to approach equilibrium values
- Xe detection limit in a flame ~130 ppm (10^{14} – 10^{15} cm^{-3})

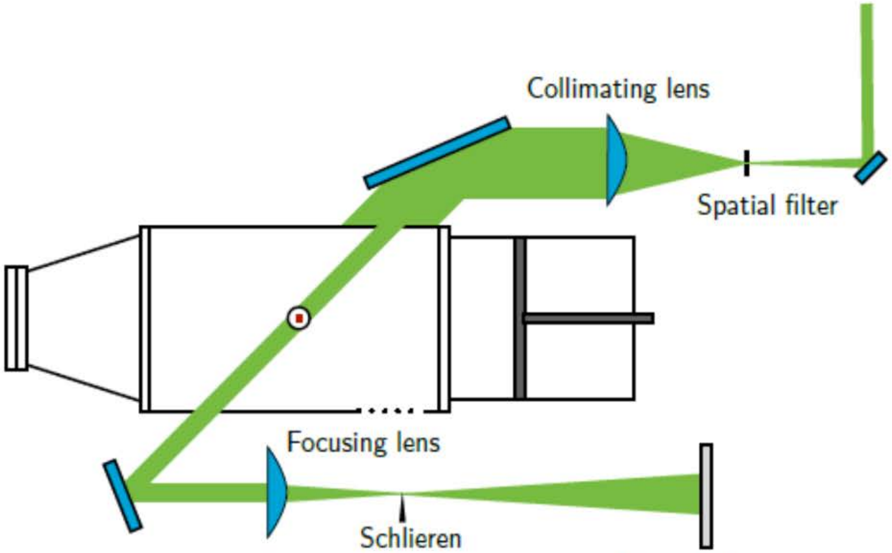
Inferred Atomic O Concentrations Using Xe Calibration



- Reasonable agreement close to stoichiometric conditions but overshoot in the fuel rich and lean regime

Schlieren imaging of Microwave coupling for laser ignition and preionization studies



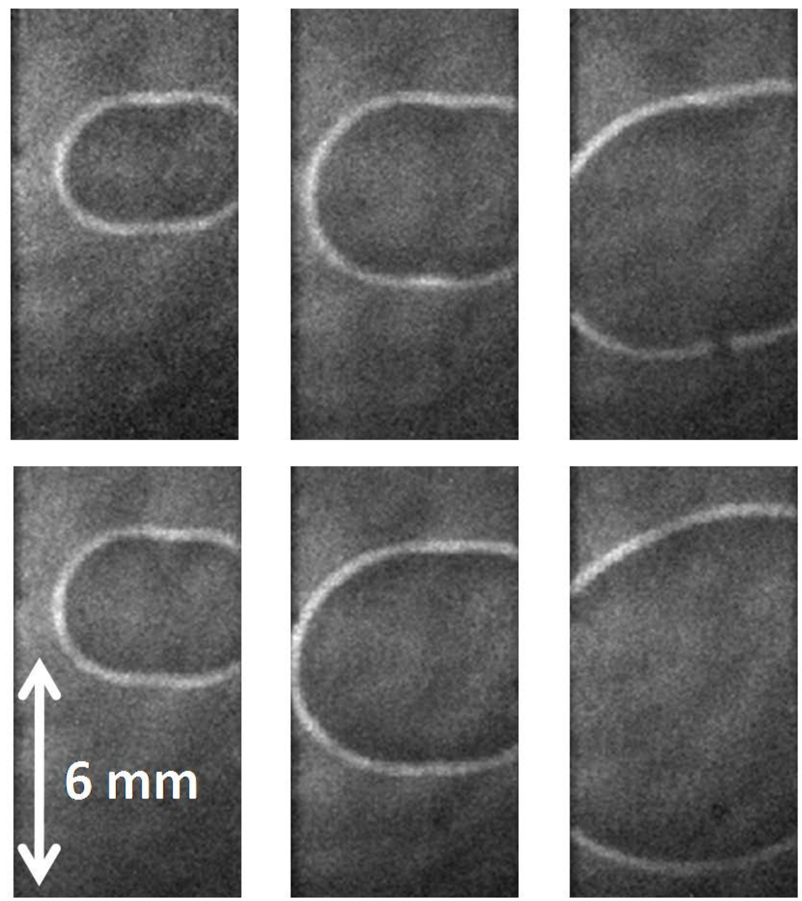


Enhanced kernel growth rate following laser designated, pulsed microwave ignition.

0.9 ms　　1.9 ms　　2.9 ms

Laser-MW ignition

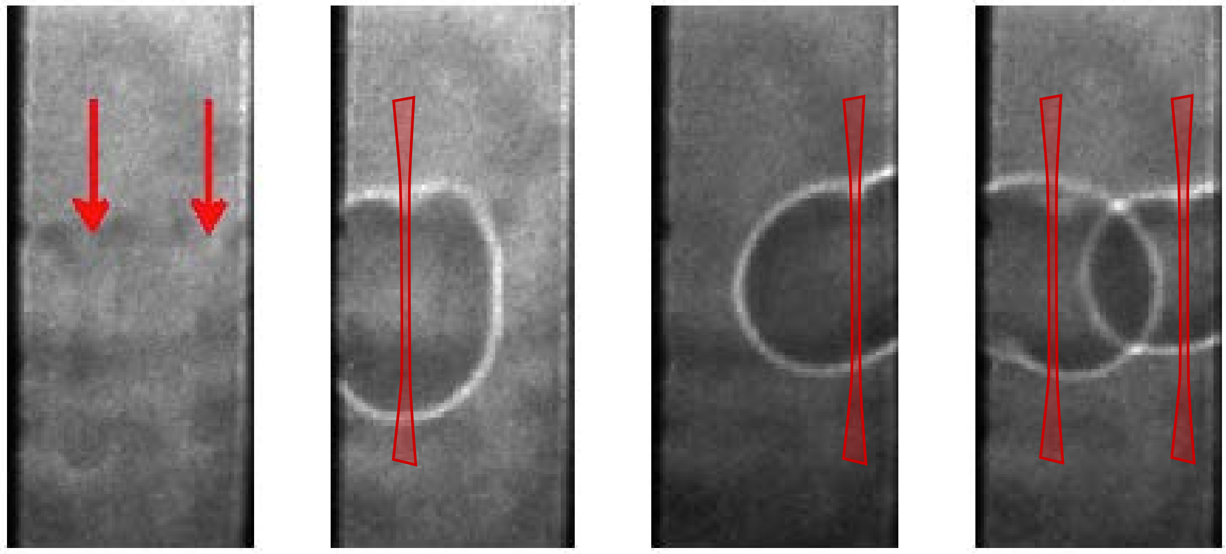
Laser-MW ignition with additional MW pulses at ms intervals.



Multi-point ignition

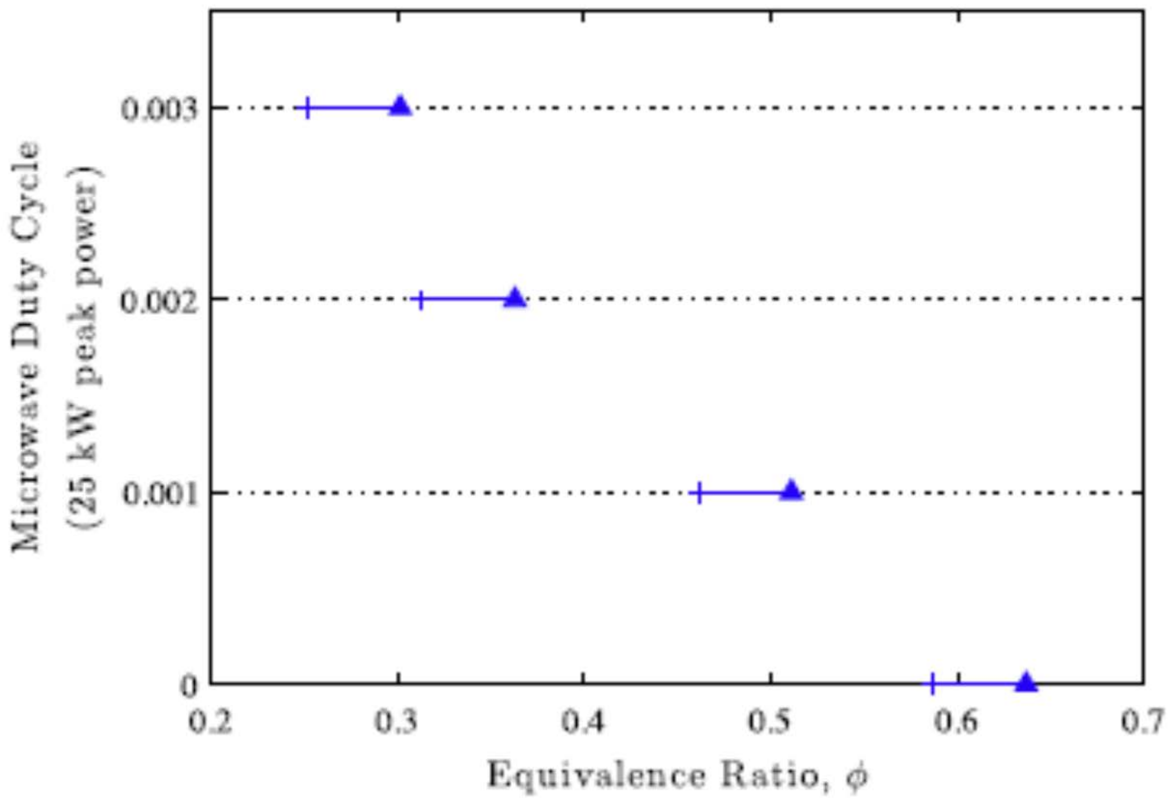
Michael, et al., Journal of Applied Physics 108 (2010) 093308.

- 2 laser ionization regions in one standing mode maximumSingle 75 mJ, 3 μs MW pulse



NO MW DUAL

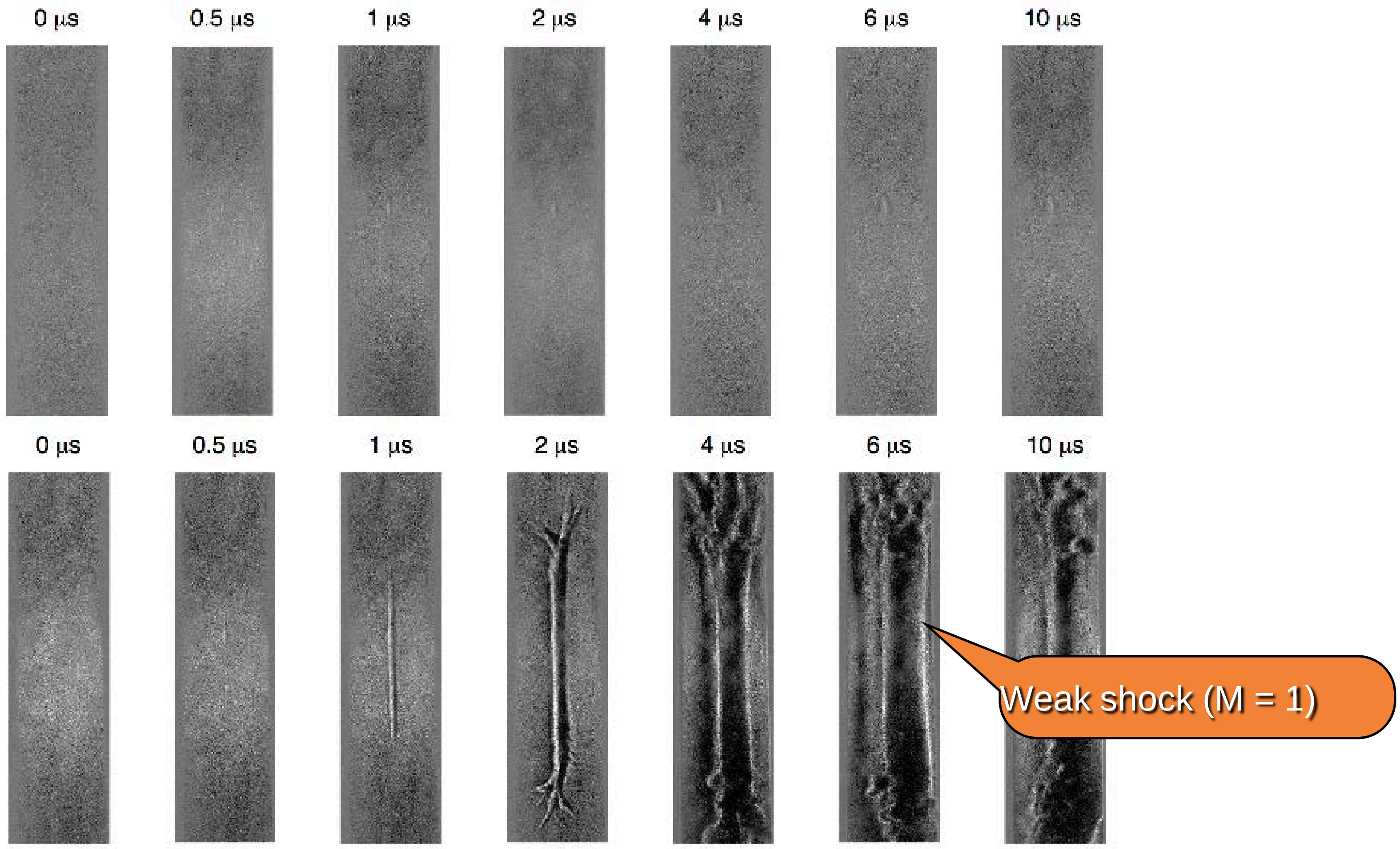
Reduction of lean limit with 1 Khz microwave pulses



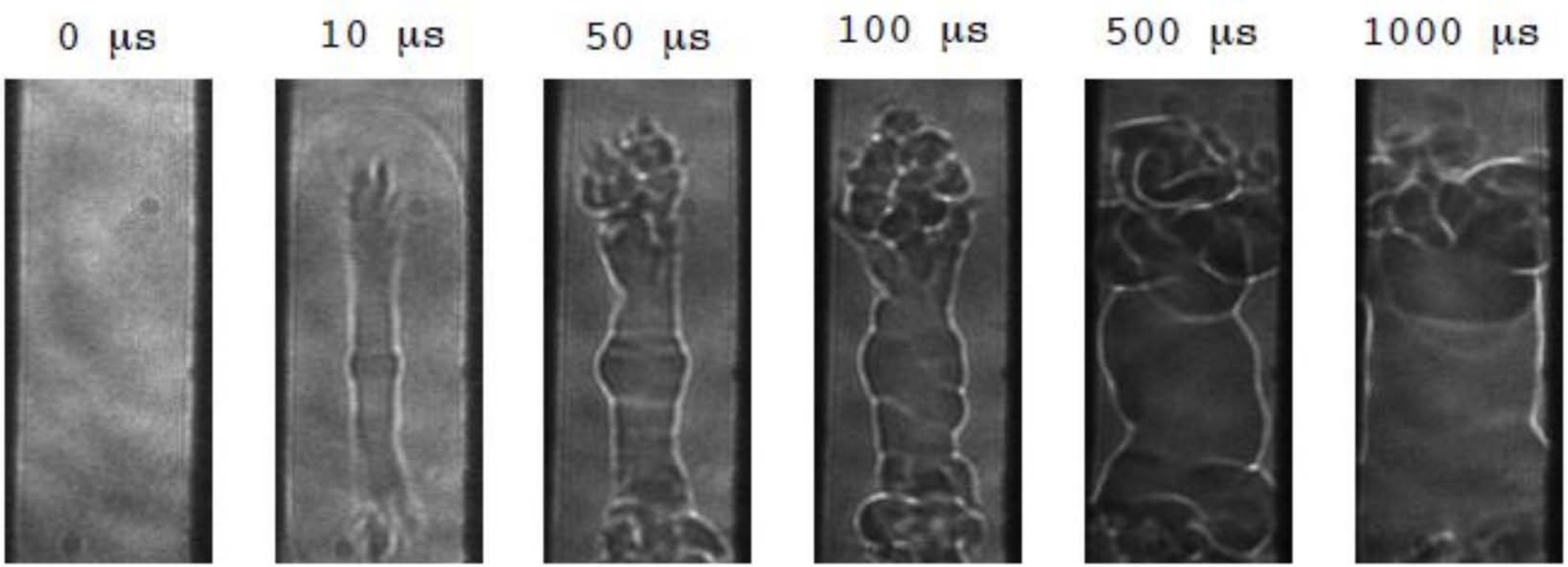
Air heating of 600 μJ femtosecond seed by Subcritical Microwave

LASER

LASER + 50 mJ MW



Line ignition using microwave coupling to fsec laser preionization line

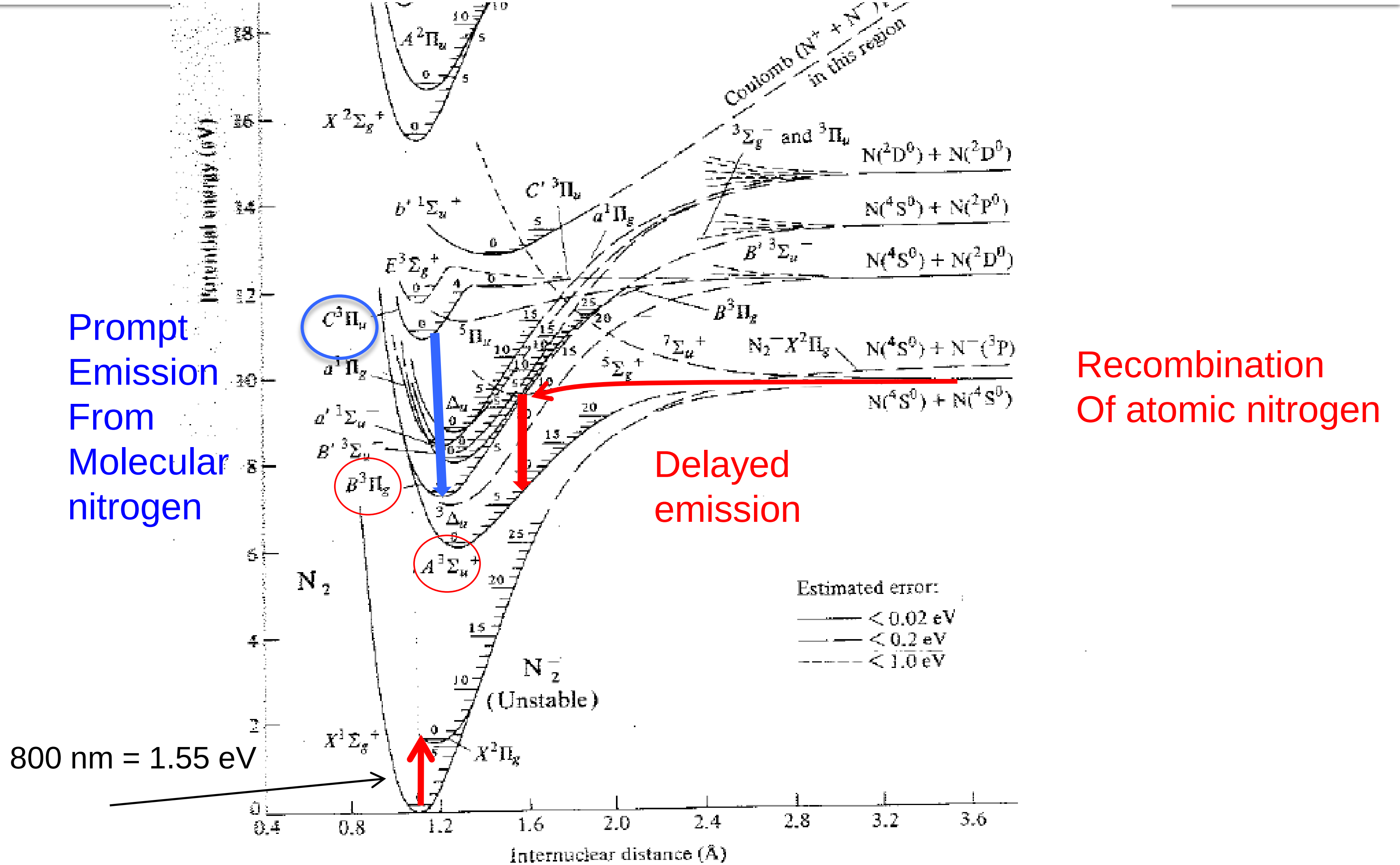


Femtosecond Laser Electronic Excitation Tagging (FLEET)

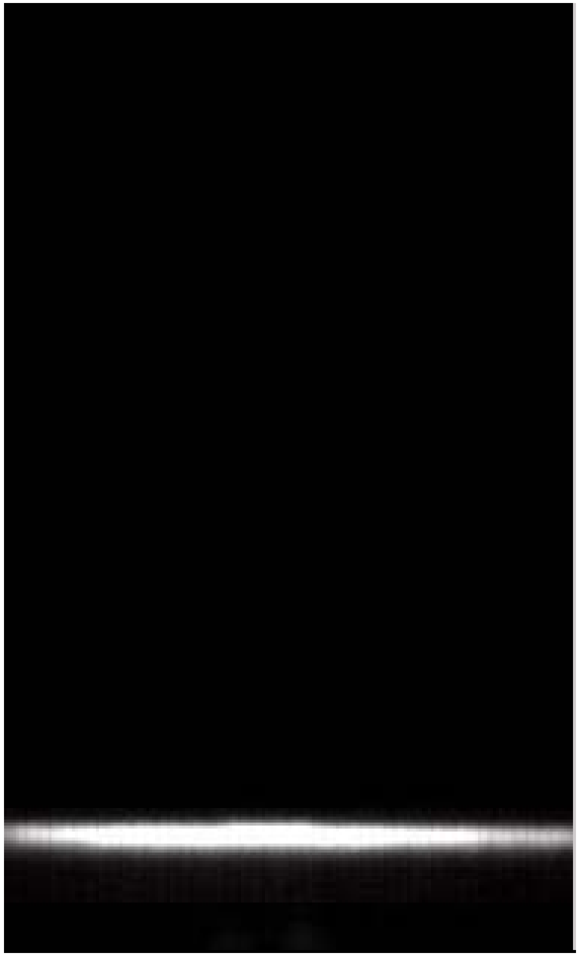
For Velocity and Temperature Profile Imaging

Applied Physics Group
Princeton University

Nitrogen Emission

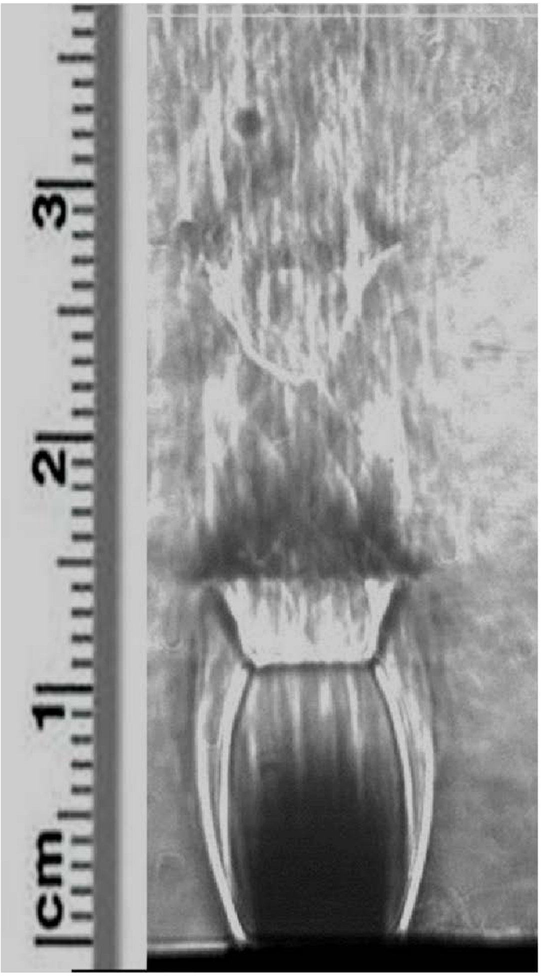


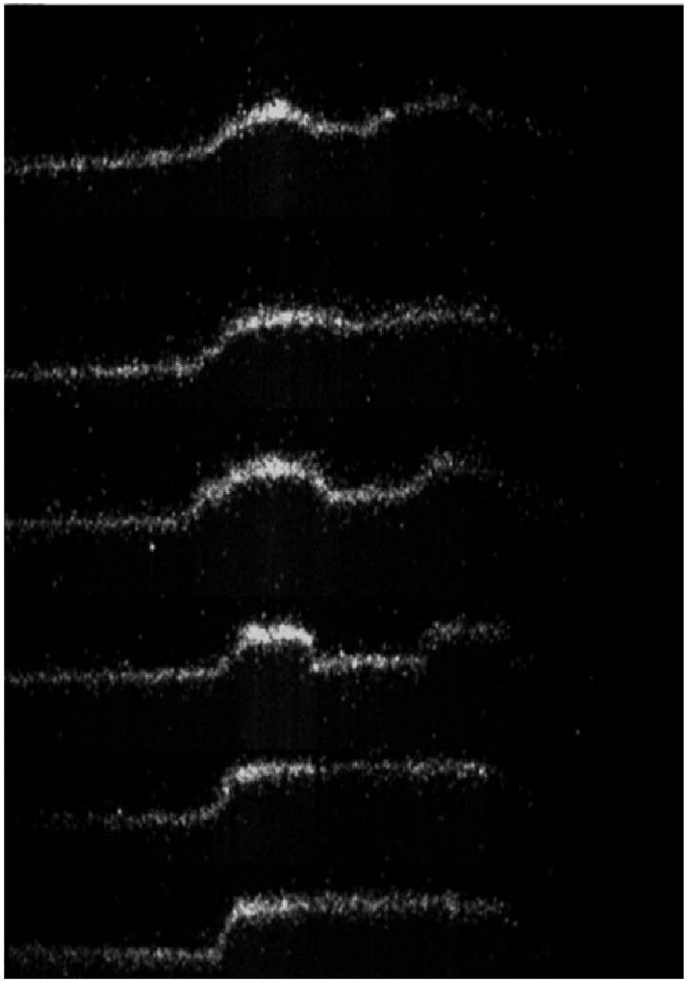
Subsonic Demonstration Video (with AFRL)



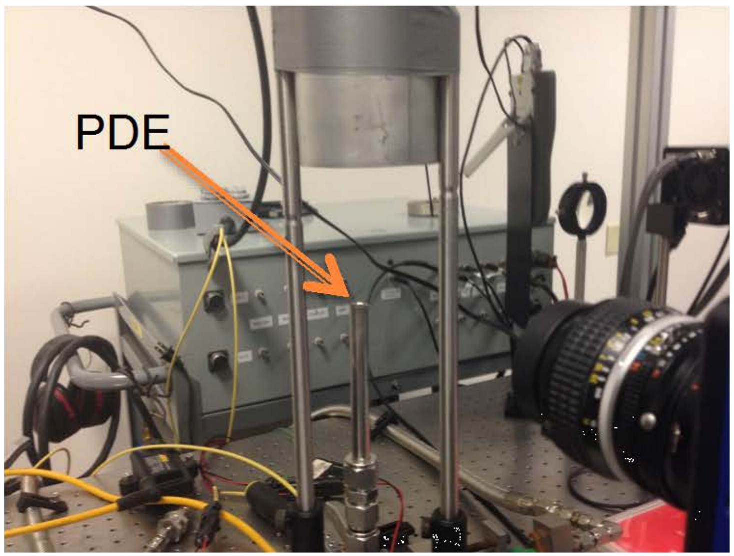
- Each progression includes about 10 line displacement shots due to the long lifetime in pure N2
- Measured centerline velocity ~150m/s

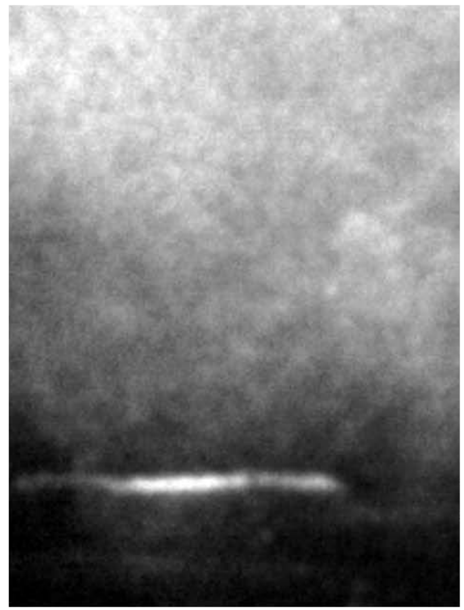
FLEET in Supersonic flow

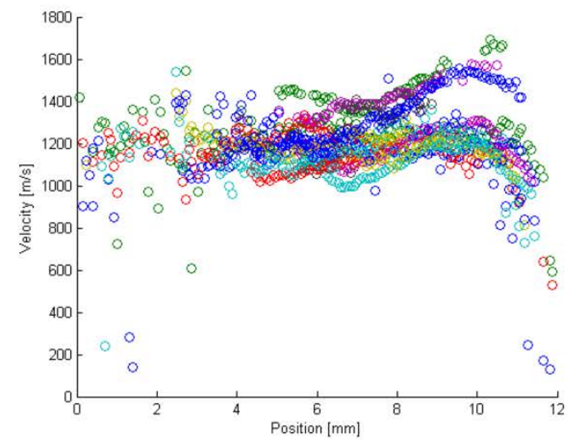




FLEET measurements of Pulse Detonation Engine at AFRL





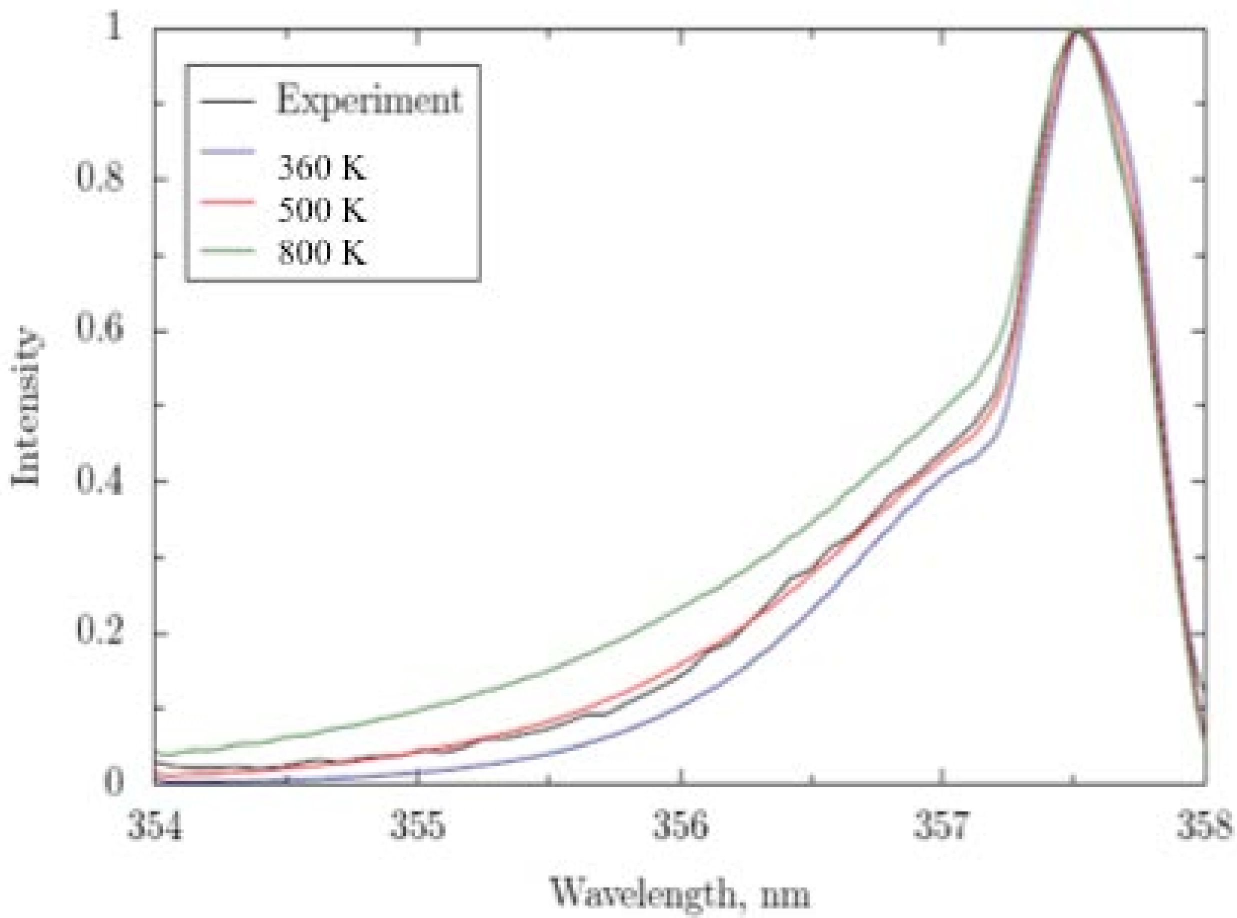


Displaced line after 1 μsec
Undisplaced line

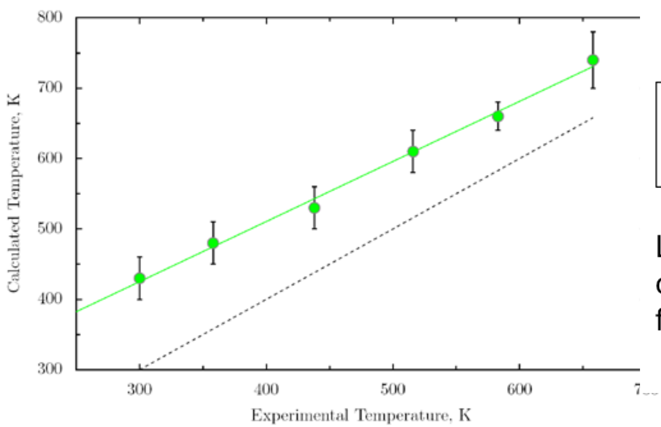
FLEET For Temperature Profiles

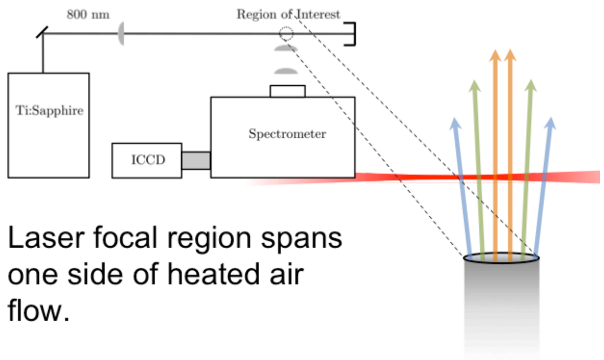
- The rotational temperature of a gas is closely linked to translational temperature.
- The rotational temperature equilibrates with the translational temperature within a few collisions – less than a nanosecond in atmospheric pressure air
- Second positive UV emission is used – prompt emission
- By measuring the distribution of rotational states, we extract the instantaneous temperature profile

Nitrogen Second Postive Spectral Variation with Temperature

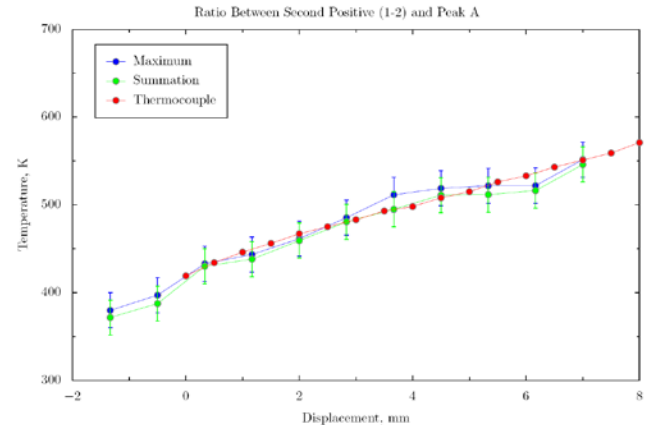


Temperature Measurement



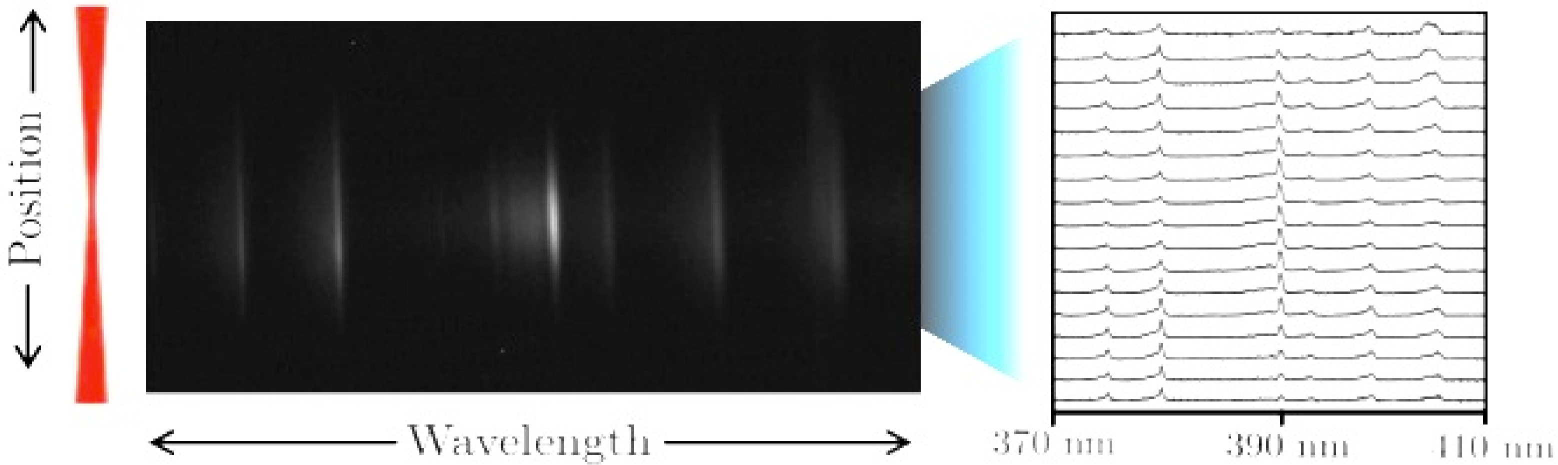


Laser focal region spans one side of heated air flow.

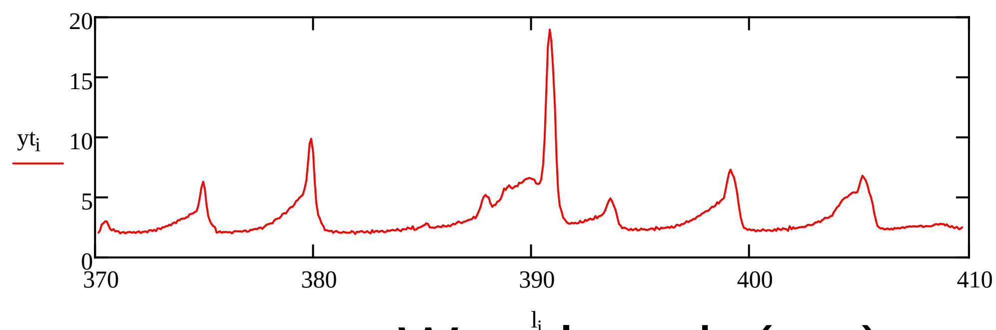


- Temperature profiles can be measured, since images capture displacement on one axis and spectrum on the other.
- Profile measurements based on ratio between systems show good agreement with thermocouple measurements.
- Temperatures calculated based on rotational spectra are slightly warmer than measured, perhaps due to laser heating of focal region.

FLEET: Hyperspectral imaging



Spectra over 4mm of filament



Wavelength (nm)

Summary

- Control of atmospheric pressure flames with pulsed microwave energy
  - High efficiency coupling (>50%)
  - Small percentage of flame power (~3% to 10%)
  - Flame speed enhancement (>20%)
  - Extension of lean limit (factor of two)
  - Distributed ignition
- Development of new diagnostics
  - Quantitative Temperature images with Filtered Rayleigh Scattering
  - Measurement of NO and radicals with Radar REMPI
  - Imaging velocity and temperature profiles with FLEET

Thank you!

Questions?